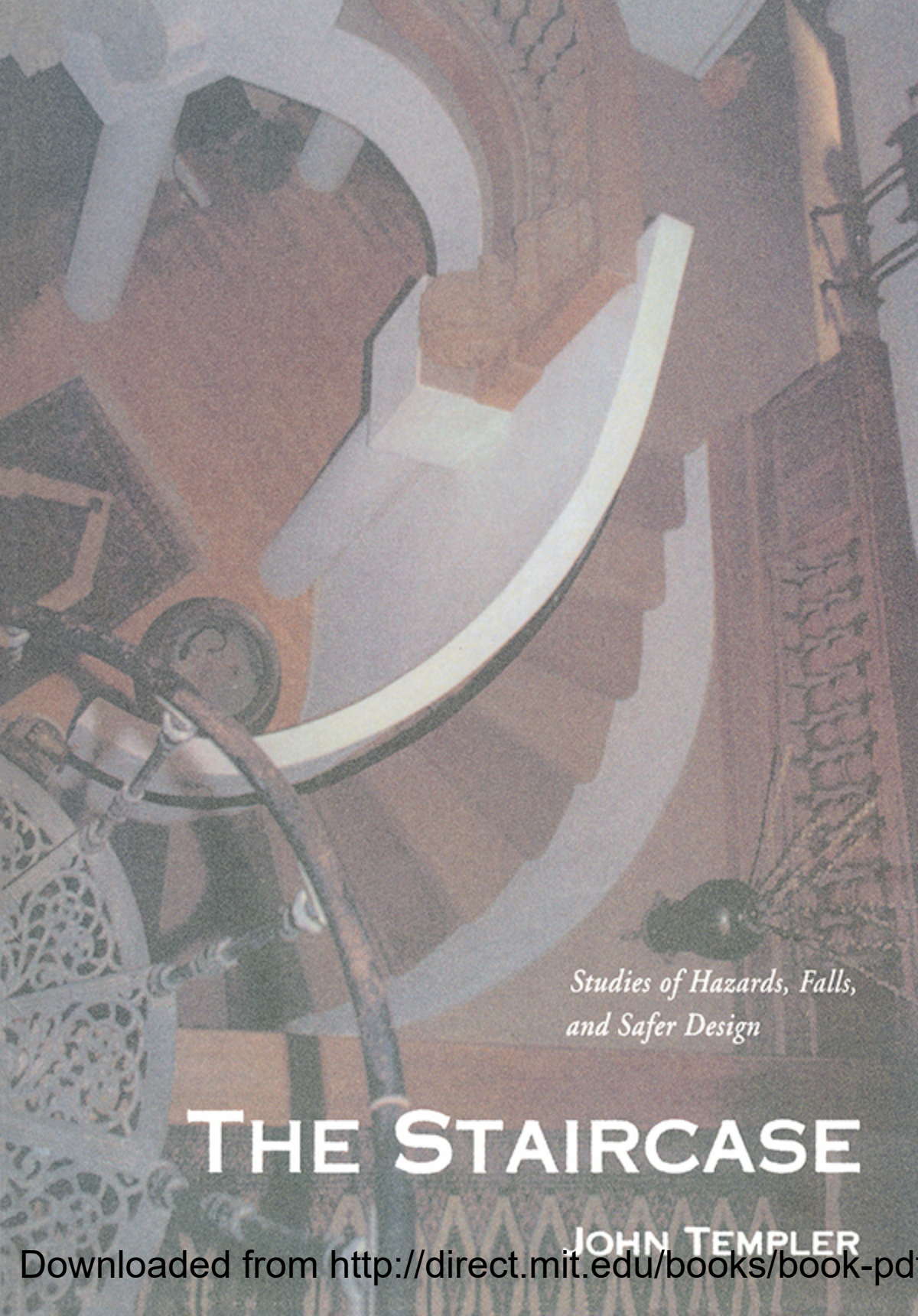

Studies of Hazards, Falls, and Safer Design

THE STAIRCASE

JOHN TEMPLER

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The Staircase

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To Huzur Maharaj Charan Singh Ji
and to my wife, Joan

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PREFACE

A poor devil has ended his cares
At the foot of your rotten-runged rat-riddled
stairs?
—Robert Browning

The stair is a delightful element of architectural theater. But it also has another face—one that witnesses millions of injurious, crippling, and often fatal accidents every year. This is a cruel face because much of the suffering is unnecessary. It reflects the ignorance, carelessness, or indifference of the building industry and, ultimately, our society. Stairs are known to be dangerous and potentially injurious, but little attention or research has been devoted to improving their safety record.

It might be interesting to compare the magnitude of the financial resources expended on investigating the causes of injuries and deaths that occur as a result of air accidents, vehicle accidents, and stair accidents every year. That automobile and air travel has become demonstrably safer over the years cannot be argued. That the stair has become safer as a result of similar endeavors cannot be argued because no one has studied the question. This is not to say that there has been no research on stair safety. There has been some, but no conscientious, continuing process of analysis, diagnosis, refinement, reanalysis, and so on. It is as if society had invested in a

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dozen small studies of automobile safety over the past century—studies that were so small in scope as to be quite unrepresentative of traffic accidents and were so underfunded that the results and recommendations were never evaluated. With this record of research, the automobile would still be the perilous machine it was at the turn of this century. The stair still is.

Automobile and airplane safety have improved by a continuous process of monitoring, analysis, and feedback leading to progressive improvements. This has occurred because of actions of the industry, spurred on by pressure and assistance from the federal government and the undoubted influence of personal injury litigation. There is no such community of interests in the building industry. There is no federal agency with a continuing mission to reduce building accidents, and the industry seems to be too fragmented to undertake such a task. The building codes suffer from the same limitations. Without the evidence of research, their provisions represent a consensus based on the well-intentioned ideas and experience of industry and code officials.

This, then, is the climate within which this volume is written. Nevertheless, on the basis of the studies that have been made, we know that there are ways to make stairs much safer. There are two synergistic approaches to stair safety: accident prevention and injury reduction. The former has been the focus of almost all the reported studies to date. Much of this book discusses the state of our knowledge of the factors that cause accidents. Using this information, there are ways to design stairs where the probability of falls is smaller.

The science of injury reduction recognizes that accidents will still occur even on the safest stair, but that the resulting injuries need not be serious or fatal. To discuss stair injury reduction is easy from one point of view. To date, there are only six published articles (Templer 1984, 1985; Templer and Hyde 1988; Templer et al. 1989; Boulet et al. 1989; Hanagud et al. 1989), and all are part of one research project. However, some of the theory and experience of injury reduction measures in automobiles is transferable to stair accidents. Accidents that injure automobile passengers are very different from those that occur during a fall on stairs, so the comparison must be limited. Nevertheless, the last part of chapter 7 discusses ways of reducing injuries. The discussion is based on reasonable premises, bearing in mind the limited research.

Stair safety is a complex subject, encompassing many disciplines. We must consider the epidemiology of stair accidents: the biomechanics of human gait, reaction time, and responses; work physiology and the energy demands in walking on stairs; etiology (the causes of accidents); kinematics (the influence of mass and force that occur during a fall); perceptual and cognitive aspects of behavior on stairs; traffic engineering and pedestrian flow and the capacity of stairs to cope with crowds; materials engineering; and the many facets of human factors engineering that relate to illumination, field and ground identification, and accident reconstruction.

Chapter 1 of this book describes the magnitude of the problem and identifies those groups of people most at risk. It also sets out to examine why people fall and what causes injuries. Much of the remain-

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der of the book discusses ways to reduce stair falls and injuries. Chapter 2 deals with the ancient debate on how big risers and treads should be for safety and comfort. Chapter 3 examines the role of slip resistance and its implications for stairs and ramps. Chapter 4 is concerned with the dimensions of flights of stairs and other factors that may render them inadequate for large crowds of people.

Chapter 5 reviews the behavioral ramifications of stair use—how people see, understand, and behave on stairs and may be misled by dangerous designs; what causes human errors; and what is the difference among risk, hazard, and danger and how these are recognized. Chapter 6 deals with handrails, balustrades, and guardrails. Chapter 7 shows how to avoid the main causes of stair falls and discusses some of the ways to reduce the likelihood of injuries caused by the parts of the stair. Chapter 8 introduces some of the legal duties owed by building designers, owners, and builders. Finally, the appendix sets out a process for making sure that a stair is to be relatively safe, comfortable to use, and properly constructed.

The story of the stair is fascinating and complex. The history of the main phases of stair design and the concepts that governed these developments are treated in the companion volume, *The Staircase: History and Theories*.

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1 THE CHARACTERISTICS OF STAIR FALLS AND INJURIES

1.1 ARE STAIRS DANGEROUS?

Stairs are manufactured artifacts like cars, soap, toys, and medicines. None of these can be utilized without some risk. Those that are poorly designed and manufactured may be so inherently dangerous that the risk of using them is unacceptably high. There are few, if any, products of our artifice that are wholly benign. We accept risks if we can assess them. We cross roads risking injury or death. We calculate that the chance of our being struck by a car is low if we are watchful and our estimation of the circumstances is accurate. We ingest medically prescribed chemicals with confidence because, so far as we know, the side effects and deleterious consequences are small in the acceptable dosages.

An unacceptably high risk is one that is unreasonable, unnecessary, and avoidable; the consequence may be injury or death. Driving a car or even walking along the sidewalk involves the assumption of a risk of a collision or a fall. However, the probability of either event's occurring is acceptably small if we observe the common cautions. Walking is risky because human bipedal ambulation requires us to be constantly off balance (four legs provides a more stable design). Therefore if we trip, slip, or put a foot wrong in various other ways, we may lose our balance and fall.

1.0 *Ruined palazzo, Palermo*

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We accept this risk because we are aware of it and have confidence in our physical agility. Nevertheless, there are risks in walking, and we lose our balance quite frequently.

When we walk or drive a car, there are certain risks we usually will not take. We will not drive a car without brakes or attempt to walk across an obviously rotten plank. If the brakes seem to be working but suddenly fail or if the plank looks quite sound before collapsing, we are in trouble. The dangers are unexpected and not assessable.

Using stairs involves risks that are greater than walking on the level because the consequences of a fall are likely to be more serious. Using a stair, however, should be no more dangerous than running, driving, riding a bicycle, or playing football. Nevertheless, we learn quite early to use stairs with appropriate caution. Most of us know that stairs are more dangerous than level floors, but this does not dissuade us from using them. One might conclude that stairs are somewhat dangerous but not to an unacceptable degree, and certainly not to the extent that we might consider avoiding them completely. In fact, in the United States, some 12,000 people die every year after a fall from one level to another or a fall on the same level (National Safety Council 1989, 6; Lambert and Sattin 1988, 21–26).[1] And this estimate may be significantly low because death certificates may not list the fall as the primary cause of death (Baker, O'Neil, and Karpf 1984, 113–127). According to the National Safety Council (1989), about 12 million people in the United States are injured seriously enough every year from falls to require at least one day of restricted activity or medical attention.

Deaths resulting from motor vehicle accidents are the largest cause of accidental deaths every year in the United States (45,000). Falls are the second largest. Falls cause more than twice as many deaths annually (National Safety Council, 1988) as drowning (5,000) or fires and burns (5,000). The U.S. Consumer Product Safety Commission (1987) estimates that in 1986, 1,464,224 people were treated in hospital emergency rooms, and 6,200 died, after being injured as a result of falls on floors, landings, stairs, and ramps in the home, where more than half of all falls occur.

In 1990 in the United States, it has been estimated that 998,871 people received hospital treatment for injuries resulting from stair accidents, and 45,948 were hospitalized (National Electronic Injury Surveillance System 1990, 15). From similar data from 1976, approximately 4,000 died (Archea et al. 1979, 1). Stair accidents serious enough to disable the victim after the day of the fall amount to between 1.80 million and 2.66 million per year. To put these figures into perspective, we should look at data from other countries. The results of studies of accidents in the home in the United States and the United Kingdom differ in some respects. However, steps and stairs turn out to be the most dangerous element in the home in the United States, the Netherlands, and the United Kingdom. In Japan, more people are treated in hospitals for accidental falls than because of traffic accidents (Kose 1982, 5). In 1976 almost as many people there died from falling on steps or stairs (541) as from fires

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(865)—and this in a country with many wooden structures.

These figures indicate that stairs as designed and built (but not necessarily as they might be designed and built) are some of the most dangerous artifacts in our environment, and they also suggest that as much research attention should be paid to stairs as to fires. In reality, fire research, fire insurance, fire codes, and fire prevention are all part of an industry with substantial resources. No comparable interest or financial support is available for studies of falls in the built environment.

That stairs have been shown to be dangerous does not mean that they are inevitably and incurably dangerous. It does mean that this epidemic of falls needs to be treated. Aspects of the disease are known. If this knowledge is used, we can ensure that stairs will be made much safer than they are now. A starting point is to consider the epidemiology and etiology of stair accidents. The paucity of the data available on stair falls means that we must rely on indications rather than statistical findings and that conclusions must be considered within these limitations.

1.2 Who Falls on Stairs?

It is probably a truism to say that everyone who walks also falls and everyone who uses stairs will fall on stairs. Most incidents on stairs are stumbles, trips, or loss of balance that are quickly and easily corrected without further consequence. Archea et al. (1979) estimate that noticeable missteps occur once in every 2,222 stair uses (a misstep is where the slip, stumble, trip, or other mishap results in a loss of balance that is corrected before a fall occurs), minor accidents occur once in every 63,000 stair uses, disabling accidents occur once in every 734,210 stair uses, hospital treatments occur once in every 3,616,667 stair uses, and related deaths occur once in every 513,947,300 stair uses.

1.2.1 Age as a Factor

Falling is an epidemic that plagues the elderly more than any other segment of the population. Three-quarters of those who die after falling are 65 years old or over. In the home, 84 percent of those who die after a fall are over 65 (National Safety Council 1989). About 1,800 fatal falls occur each year in residential institutions (Baker et al. 1984). Children, on the other hand, seldom die from a fall on stairs.

No studies, however, discuss the frequency with which the various age groups use stairs, and only one discusses injury severity. The elderly tend to avoid stairs, so they may be underrepresented in these statistics.

1.2.2 Sex as a Factor

Females have more stair accidents than do males. However, when we look at age as a factor, we find that male children up to the age of about 14 fall more frequently in the home than do females. In nonresidential settings, after the age of 5, males (in Japan) fall more frequently than females do.

The high accident rate for adult females is probably a reflection of the fact that most stair accidents occur in the home, and adult females still spend more time in the home than adult males do while there are more males in nonresidential (work) places. There is, however, some indication that elderly women step down with an action that provides less muscular control (Azar and Lawton 1964, 83). In public (nonwork-

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place) settings, no significant difference in the accident rate for males and females is found.

1.2.3 Marital Status

An examination of the distribution of falls experienced by unmarried, married, or previously married people reveals that the last are overrepresented. This is not only among the elderly, an expected finding, but among all age groups. Unmarried people aged 40–49 are also overrepresented.

1.2.4 Physiological Factors

One might expect to find that people with physical and medical disabilities are more likely to fall than other people. Several studies, however, have shown that dizziness, high blood pressure, and poor hearing do not add to the risk of falling. Even the problems usually associated with age—impaired vision and reduced mobility—do not appear to add to the risk. In fact, fall accidents are more frequent among people with cardiovascular diseases than among people with diseases of the joints. The incidence of falls in relation to various physiological conditions is an area of research now receiving more attention from epidemiologists.

1.2.5 Characteristics of the Household

In a study in Holland (Heimplaetzer et al. 1988, 186), it was found that adults in households with younger children have more accidents than those in households without children. The authors concluded, however, that this may be the result of a higher frequency of stair use.

1.2.6 Alcohol and Substance Abuse

Alcohol consumption may induce stair falls. From Svanstrom's study (1973), about 16 percent of people who fell on stairs had consumed alcohol immediately before the accident. About 14 percent of these said they were clearly intoxicated when the accident happened. Most of these alcohol users were aged 20–49; 35 percent of stair fall victims of these ages had consumed alcohol just before the accident.

1.2.7 Accident Proneness

Accident proneness is a term coined in the 1920s to describe a tendency to be involved in risky behavior. The idea is controversial. Only one study of stair accidents in relation to accident proneness and stair use has been reported. Svanstrom (1973) found that 42 percent of the victims in the study had fallen down stairs previously. He concluded that "this can partly be seen as a sign that accidents on stairs are very common, but might in itself possibly support a theory about 'accident proneness,' in that some persons are more *exposed* to accidents than others [my emphasis]. Most of these fell when they were children, 53% were namely under 17 years of age when the last registered accident happened on the stairs." It may also be that young people are simply less skillful at negotiating dangerous stairs—those with accident-inducing defects.

From the epidemiology of stair falls, it might be tempting to conclude that anyone who is female, a young male, elderly, previously married, or unmarried between the ages of 40 and 49 and, perhaps, has just consumed alcohol is fated to fall. This is obviously nonsense. The overwhelming majority of these people will not fall when they use stairs, even if they are under the influence of alcohol.

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1.3 Where Do People Fall on Stairs?

Studies in the United States, Japan, and Sweden have shown that most stair accidents occur in the home (in the United States 80 percent of all stair falls, in Japan 68 percent, and in Sweden 72 percent). In Sweden, most of these stair falls (58 percent) occur in the victims' own homes. Of those accidents that do not occur at home, in Japan more than half (54 percent) occur in shops, restaurants, or railroad stations. In the workplace in the United States, falls on stairs have been found to be one of the major causes of compensation claims and lost work hours (Cohen et al. 1985, 171). These statistics explain why most of the studies of stair accidents have concentrated on the workplace and the home. Table 1.1 shows the distribution of stair accident locations in one study. Nearly three-quarters of all stair falls in Malmö, Sweden, were in houses. Table 1.2 shows the type of workplace where stair falls occurred (in California and Ohio) and their incidence.

1.3.1 Indoors or Outdoors?

In Sweden, Svanstrom found no difference in the percentage of accidents occurring on outdoor stairs and on indoor stairs. On the other hand, Cohen et al. (1985, 173) found that twice as many of the work-related accidents occurred inside as outside, although the results vary by state. They found little difference between indoor and outdoor rates in Ohio. However, in California, 70 percent of the accidents were indoors. Probably the climatic differences explain the variation. In cold climates, as one might suspect, more of the falls occur outside.

Table 1.1

Place Where Stair Falls Occurred

Location	*Number of Falls*	*Percentage*
Multifamily house	*110*	*50*
Detached terrace house	*53*	*24*
Office, shop	*15*	*7*
Industry	*5*	*2*
Public building	*21*	*10*
School, nursery	*11*	*5*
Hospital	*4*	*2*
Total	*219*	*100*

Source: Svanstrom (1973).

Table 1.2

Workplaces Where Stair Accidents Occurred

Site	*Number of Falls*	*Percentage*
Office areas	*169*	*27.9*
Manufacturing	*106*	*17.5*
Retail stores	*45*	*7.4*
Schools	*38*	*6.3*
Restaurants	*35*	*5.8*
Hospitals	*28*	*4.6*
Warehouses	*9*	*1.5*
Construction sites	*39*	*6.4*
Private residences[a]	*14*	*2.3*
Private residence entrances[a]	*25*	*4.1*
Miscellaneous job sites	*37*	*6.1*
Emergency response sites	*10*	*1.6*
Others	*21*	*3.5*
Unspecified	*29*	*4.8*
Total	*605*	*100*

[a] *Accidents where the workers were working at residences.*

Source: Cohen et al. (1985).

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TABLE 1.3
Location of Workplace Stair Falls

Site	Number of Falls	Percentage
Entrance/exit	*97*	*43.1*
Basement/attic	*51*	*22.7*
Lunchroom/lounge	*21*	*9.3*
Parking structure/lot	*9*	*4.0*
Machine steps	*27*	*12.0*
Restroom stairs	*5*	*2.2*
Loading dock	*9*	*4.0*
Trailer steps	*6*	*2.6*
Total	*225*	*100*

Source: Cohen et al. (1985)

1.3.2 At What Locations Do People Fall?

The study by Cohen et al. (table 1.3) shows that a large percentage of workplace stair falls occur at entrances. The authors suggest that this can be attributed to the "unique problems faced by stair users at entrances and exits," including abrupt change of environment and visual cues from inside to out; abrupt change in level, surface materials, and conditions (many of the Ohio cases involved slips on ice and snow while leaving work); increased traffic volume as a result of funneling at entrances and exits; and haste due to lateness in reporting to work or eagerness to leave.

1.4 Why Do People Fall on Stairs?

There is a widely held view that people fall because they are careless and that nothing and nobody is to blame. It is clear from many studies, however, that people fall on stairs because of several known factors acting singly or in concert. Some of these accident-encouraging factors result from the way the stair is designed, some from the way it is constructed or maintained, some from the environments in which the stair is set, some from the way in which people use stairs, and some from the characteristics of the stair users. As the number of accident-encouraging factors present increases, so does the likelihood of accidents. In this respect, a stair can be compared to an automobile. The more mechanical defects that are present, the more traffic, the worse the condition of the road and the weather, and the greater the number of errors made by the driver, the greater is the likelihood of an accident.

For designers and planners, stair safety is not one problem but two: avoiding the circumstances that cause accidents and designing stairs that will minimize injuries if an accident occurs. Before addressing the questions of safer and more forgiving stairs, one must first understand what causes people to fall and then try to understand what happens during a fall.

People fall because they lose their balance irretrievably; no postural correction enables them to remain on their feet. Their normal gait is interrupted, and their center of gravity moves out from the base provided by their feet. Therefore, we must start by looking at the actions that we take as we traverse a stair routinely and in safety, and at what is necessary to permit this to occur. This examination will identify factors that interfere with normal stair use and lead to incidents.

Our actions on stairs can be divided into two parts: our actual climbing action or gait and the sensory and cognitive processes that we utilize to understand the steps and the stair. In reality, these actions are synchronous (although cognition is pre-

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paratory to using the stair ahead as well as the steps we are on) and synergistic.

Because of the very different gait we use on stairs, the etiology of accidents here differs significantly from that of accidents resulting from falls on the level. Walking (or running) on the level presents the body with a rhythmic cycle characterized by continuous postural instability as the center of gravity moves ahead. In walking, we appear to lose our balance regularly and then regain it. On stairs, our gait is even less stable. We balance ourselves on one bent leg as the other one swings forward and to one side to take the next step. By comparison to walking on the level, this is a slow-motion activity. It is this exaggerated gait, coupled with the increased precision demanded, that makes stairs such a balancing act on an obstacle course.

After the age of about 7, humans have mastered this movement for walking on the level so completely that the process becomes automatic, extremely efficient mechanically, and functionally free from incident. Trips, stumbles, and falls occur largely through misjudgment or dangerous and unexpected conditions in the surface terrain. If the ground is spacious, regular, and not likely to cause one to slip, then no special caveats are observed. The senses are relaxed, and the speed of forward motion may be freely chosen.

Movement on ramps becomes more demanding from this point of view as the pitch increases. Greater effort is required, which reduces the range of speeds, even in descent, because balance is more difficult to sustain, and the coefficient of friction between foot and ramp becomes increasingly critical as the pitch is increased.

Steps present a regular sequence of barriers to be negotiated. They demand a higher level of sensory alertness and general caution. Also, the geometry of the stair controls the body's movement to a much larger extent. Speed, gait, posture, pacing length, and stepping rhythm are far more circumscribed during ambulation on stairs than on inclines or on the level.

1.4.1 Normal Gait

To understand stair falls, we must consider normal human gait and then examine the factors that may act to disrupt it. People walking on stairs, on the level, and on inclines exhibit similar but personal gaits. Some people climb without their heels ever touching the tread. Others exhibit remarkable regularity, while some seem constantly unstable. Some are regular with one foot and less so with another. Height, weight, age, sex, culture, physical dimensions, and personality, among other variables, affect the style. Nevertheless, these peculiar characteristics are comparatively minor eccentricities that obtain within the generalized pattern of gait engendered by the human bipedal ambulatory mode.

1.4.2 Gait in Level Walking

For walking on the level (fig. 1.1), a gait cycle includes the activity that occurs between heel strike of one extremity and the subsequent heel strike of the same foot—the toe-off, swing phase, heel strike, and stance phase. In normal level walking, the shock of the impact is progressively absorbed as the load rolls across the foot from heel to toe.

1.4.3 Gait on Stairs

On stairs and on steep ramps, the heel is seldom the first portion of the body to

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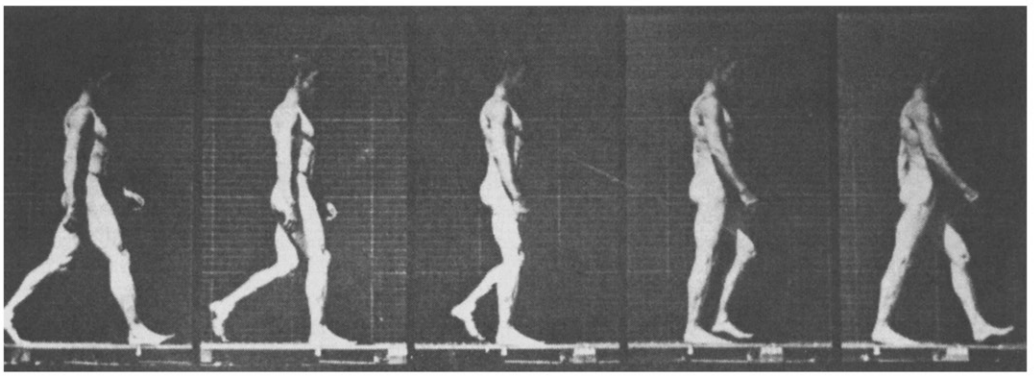
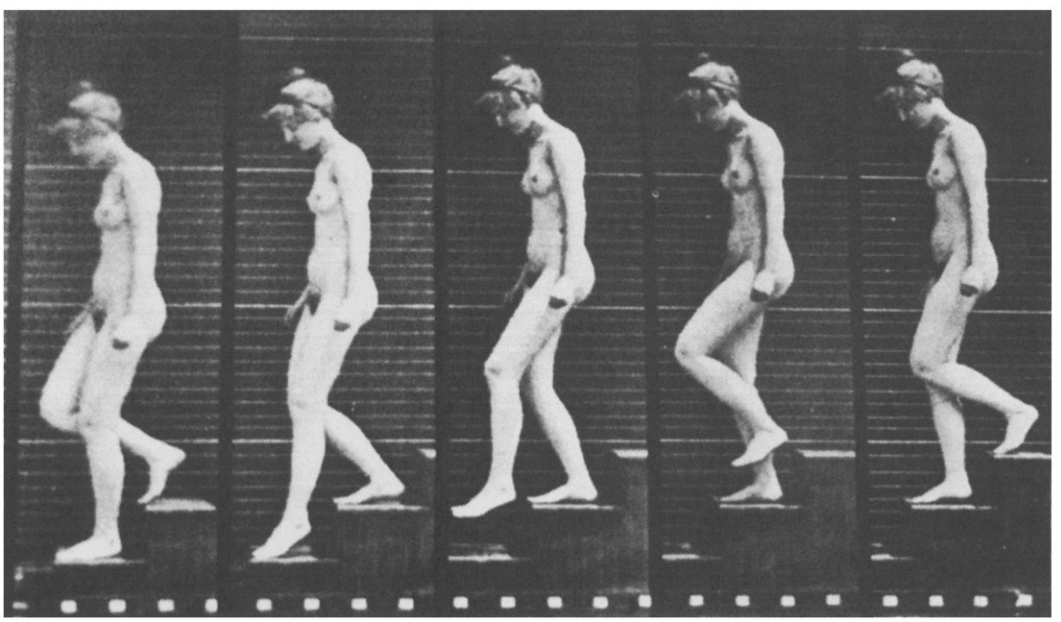


1.1 *Gait cycle, level walking, reprinted from Muybridge (1955), 3*



1.2 *Gait cycle, stair descent, reprinted from Muybridge (1955), 121*

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make contact, particularly in descent. Descending on the heel would jolt the body. To avoid this, in stair descent (fig. 1.2), the impact is usually absorbed by taking the load onto the ball of the foot, the metatarsal heads, and gradually lowering the heel to the step. This process is affected by high-heeled shoes, and the body's natural resilience is thereby diminished. (Where the riser is very small and the tread large, a gait similar to that used in level walking may become possible; however, small risers may be dangerous, for reasons discussed later.)

The gait cycle on stairs therefore must be considered as the activity that occurs between first contact—toe, foot, or heel—and the subsequent first contact by the same foot. During this gait cycle, after first contact, the body passes through one supporting or stance phase, one toe-off and one swing phase. The stance phase begins as first contact with the step is made by the leading foot. At mid-stance, the body weight is directly over this leg and is starting to be elevated or lowered by it. The stance phase continues for as long as the foot remains in contact with the tread—until toe-off. The stance phase accounts for about two-thirds of the whole gait cycle (Joseph and Watson 1967, 774–780). In the swing phase, the leg must accelerate to overtake the body and then decelerate after mid-swing, to position the foot for contact with the next step. The swing phase occupies about one-third of the gait cycle.

1.4.4 Posture

Ambulation on any incline demands a postural change. The body cannot maintain an angle perpendicular to the slope but must be adjusted forward for ascent and backward for descent in order to maintain the center of gravity over the base, the feet. The extent of the adjustment is related to the pitch of the incline. The forward lean in ascent enables the front leg to lift the body upward. This would be functionally impossible otherwise. In descent, the backward lean must be maintained to prevent one from falling forward.

1.4.5 Descent Gait

Descending stairs demands a gait quite different from ascent. If we could dedicate stairs for ascent or descent only (as in the Paris Métro), the designs should or could be quite different. Furthermore, the types of accident and injuries that result from ascent falls are different from those in descent.

As we take our first step in descent (fig. 1.2), the leading foot swings forward over the nosing edge (swing phase) and stops its forward motion when it is directly over the tread below. As this foot starts its descent, the heel of the rear foot begins to rise from the previous tread (or landing), leaving the weight of the body to be supported on the metatarsal heads of the forward foot (stance phase). At the same time, the rear leg begins to bend at the knee and the hip. In effect, we now commit ourselves to the forward foot and start a controlled fall forward and downward toward the tread. The toe of the forward foot is pointed down somewhat in order to begin to absorb the force of the fall as soon as it makes contact with the tread. The higher the riser is, the more the toe is pointed; the lower the riser is, the more the foot is kept horizontal. As the foot is lowered onto the step, the shock of the impact is cushioned by the ball of the foot. Finally, the heel descends onto the tread, so the force of the jolt is gradually cushioned

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as the body's full weight is transferred onto the forward foot. The rear foot then begins to swing forward, and the cycle is repeated. Because older women tend to let the foot drop with less muscular control and with a falling movement, the foot may hit the ground harder.

The large bones of the foot—the metatarsal heads—make the first contact with the step. Obviously the metatarsals must land on the step, not protrude beyond the nosing. In overstepping, too much of the foot projects beyond the nosing; the body's full weight is transferred to the leading foot, which may slide over the edge, causing a loss of balance. The suddenness of this overstep gives us little time to recover, and we may pitch forward.

When the foot is lowered onto the step, it has little or no forward motion but some sideways motion as we sway from side to side. In fact, forward motion on stairs, even if we run, is quite slow compared to walking on the level or on ramps. Walking at a normal-to-brisk pace on the level, we travel forward 3.5 to 4.5 feet (1.0–1.4 m) per second. On a stair, 1.5 feet (45 cm) per second is a normal horizontal speed. Furthermore, in walking on the level, forward motion remains more or less constant. Movement on stairs is characterized by a repeating action of acceleration and deceleration. The body accelerates forward, then decelerates, and virtually stops as the foot is lowered onto the tread. The pelvis tips down toward the side of the swinging leg (up to a maximum of 10 degrees), so the probability of a slip at this moment is not great—contrary to popular belief—unless the nosing area of the step is slippery. The probability of a slip when walking on the level is much higher because initial contact is made by the rear edge of the heel traveling at full speed.

There is some risk of a slip when the leading foot has been brought down onto the step, all the weight has been transferred to it, and the other leg is swinging past it at full speed. Some of the inertia of this movement is transferred to the stationary foot. However, natural caution acts to limit this, and we hold our center of gravity as far back as we can during descent by leaning back somewhat. In walking on the level or ascending stairs, we lean forward.

There is also some risk of a slip as we tilt up the heel and lift the rear foot off the step preparatory to starting its swing phase, although the risk is small because the horizontal motion during lift-off is small or nonexistent. We do not need to push off with the rear foot as we do in level walking in order to move our center of gravity forward. In fact, the most serious problem during this swing phase occurs if we catch our heel or shoe against the riser or, more likely, the nosing, because the foot becomes locked in place, and we lose our balance. As Harper and his associates (1967) observed, catching the heel on the riser in this way is one of the dangers inherent in stairs with high risers, narrow treads, and projecting nosings.

On stairs, our base from the heel of the rear foot to the toe of the front foot is usually no more than two treads—24 inches (61 cm) for those with 12-inch (30 cm) shoes—whereas on the level, the base is our pace of about 30 inches (76 cm), so on stairs we can start the forward movement by simply leaning forward to move the center of gravity through the 12 inches (30 cm) or so of each step. As the forward foot

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is lowered to the step ahead, the rear leg carries all the weight. We balance on this one leg, which must then bend at the knee and, to a lesser extent, at the hip simultaneously to allow the forward leg to reach down to the step ahead and below. This is the most critical moment in the descent: we teeter on one leg with a bent knee, tilting the pelvis sideways and down, as we raise the other foot off the step behind and swing it forward to the step below. In a sense, we are hurrying to get the swinging leg back down on the ground again to restore our balance. If anything goes wrong during the swing phase, the probability of a fall is substantial. Not only is our leg swinging forward but so is our whole body. If we catch our toe in the stair carpet, catch our heel on the nosing edge as we swing past it, or overstep the edge, we may well be projected forward out of control.

To maintain a safe and comfortable gait, the whole motion has to be continuous and rhythmical. To walk very fast on steps is nearly as difficult as to walk very slowly. In fact, we may prefer to take the steps two at a time if we want to hurry. To descend very slowly is a challenge to our ability to stand on one leg for any length of time. This is why young children whose legs are too small to manage a rhythmic gait on stairs made for adults, and elderly or disabled people with stiff joints, struggle to maintain their balance on stairs. This is also why the handrail is not just a safety net for them but a crutch.

1.4.6 Ascent Gait

Serious injurious falls incurred during descent outnumber those in ascent. This does not mean there are more accidents in descent, but the consequences of an accident in ascent are perhaps less likely to be serious enough to require medical treatment. In ascent, the center of gravity is held slightly forward and any mishap usually (but not always) means that the victim falls forward toward the steps, which are literally close at hand.

In ascent, the gait (fig. 1.3) still encompasses a toe-off, a swing phase, first contact, and a stance phase. At first contact, the leading foot is lowered onto the next step up but with the foot roughly horizontal. The ball of the foot is usually placed well forward on the tread, and the heel may or may not be placed on the tread. The foot possesses little residual forward motion and some lateral motion as the pelvis sways from side to side; therefore, there is only a slight risk of a slip. There is some risk of understepping—missing the next step entirely or slipping off the edge because not enough of the foot has been placed on the step—actions that are likely to project us suddenly forward toward the steps.

After the forward foot is in place, the rear foot begins to rise onto tiptoe to help lift the whole body vertically upward and forward. The forward part of the foot or shoe is therefore pushing down and back against the tread. We may slip if there is inadequate frictional resistance between shoe and step. The push off from the step is quite vigorous to make it easier for the thigh muscles of the other leg to straighten the leg and to lift the body. Simultaneously, the rear leg begins the phase in which it is raised and swings past the forward foot onto the step above.

As with descent, the swing phase is the most troublesome. We stand on one bent leg, which we must straighten while we raise our whole body up the 6 to 8 inches

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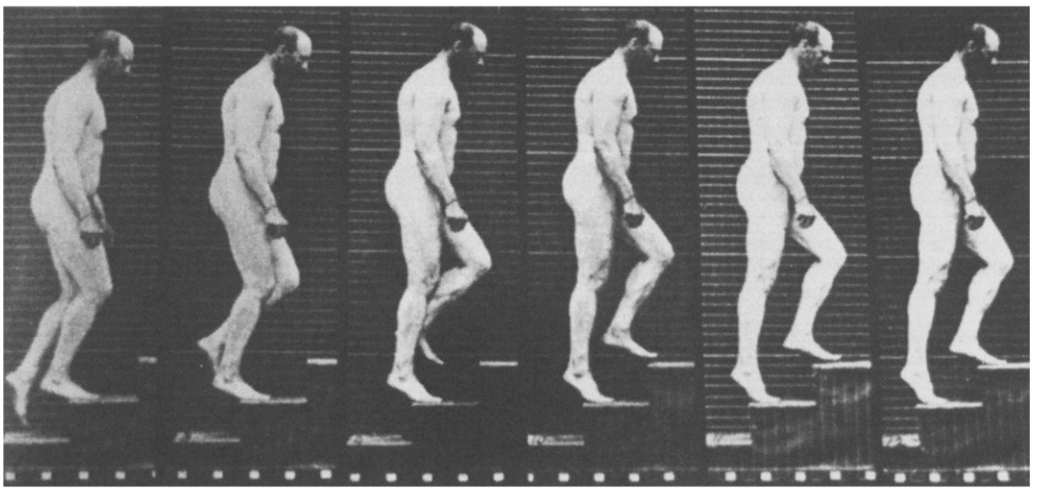

1.3 *Gait cycle, stair ascent, reprinted from Muybridge (1955), 13*

(15–20 cm) of the riser, move our center of gravity forward about a foot (30 cm), lift the other leg and foot up the 12 to 16 inches (30–40 cm) of two risers, and try to find a rather narrow ledge on which to seek a new footing. The risk is that we catch our foot, toe, or heel on one of the two stair nosings that the foot must pass, tripping us up and projecting us forward. Because the effort required to lift the foot is proportional to the riser height, the higher this is, the greater the likelihood there is of a trip. Risers higher than 8 inches (20 cm) are quite uncommon except for ladders and ship companionways. The rung spacing of ladders is usually about 12 inches (30 cm), and to climb this height, we use our hands to help pull us up. Ascent demands physical strength, as well as agility, and this compounds the problem of balance for the old, the young, and those with disabling conditions.

1.4.7 Inattention to the Stair

Whatever disturbs our gait increases the risk of a misstep, a loss of balance, or a fall. Gait on a stair is not an autonomic or mechanical activity that takes place without deliberate and sometimes conscious interaction with the mind. Obviously the mind controls our gait. If our gait is disturbed (unless we are pushed, or the building falls, or some similar event that is beyond our control), then either our skill has failed us or we have misunderstood the stair, or both.

Walking on a stair requires skill that can be compared to playing with a bat and a ball. If eye-brain-arm coordination is always perfect, we can slug the ball solidly every time; however, we are imperfect and sometimes fail. Furthermore, some people have highly developed athletic skills, and some do not. All of us have times when

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we can hit that ball every time and others when we curse ourselves for our clumsiness.

Before we shrug off any stair accidents as a consequence of fallibility, we must ensure that we are refereeing the game fairly. If, for example, dusk prevents us from seeing the ball clearly, or the ball or bat is too small, the bat is too short, or half a gale is blowing, we must expect our hit rate to decline. And so it is on stairs. The stair and its surroundings may be so bad that the dice are loaded against us before we take our first step. When this occurs, we can hardly blame an incident on the diminished skill of one who plays the stair game. We expect to play with dice that are not loaded and stairs that have no secret deceits.

Putting aside for a moment the image of the victim as a klutz, the cognitive condition that may lead to successful or failed stair use must be scrutinized. We will return later to the klutz and see what can be done to sharpen his skills and protect him from himself if all else fails.

1.5 What Factors May Cause Stair Falls?

Following is a partial list of factors (not ranked) known to cause stair falls.[2] (Each of these factors is treated in chapter 7, where avoidance strategies are discussed.)

User behavior:

- hurrying, running, slow gait
- not paying attention, distraction
- playing on the stair
- carrying things
- misjudging number of steps
- misjudging location of nosing

Stair maintenance:

- ice, snow, water, other substances on treads
- articles left on stairs
- broken tread
- loose or torn carpet or covering
- tread badly eroded
- light broken or not switched on
- loose nosing strip
- absent or broken handrail

Stair design and construction:

- a single step
- narrow treads
- dimensional irregularity
- inadequate illumination
- risers that are too high or too low
- a step or stair in an unexpected place
- no handrails
- nosing strip that projects above the tread
- slippery tread material
- distracting views
- confusing patterns on the tread

1.6 What Types of Accident Occur?

Two studies of videotape recordings of people walking (and falling) on stairs (Templer et al. 1978; Templer et al. 1985) enable us to classify the major causes of balance loss that result from the accident-inducing factors.

Balance loss during ascent:

- catch toe (or heel) on nosing; trip
- understep (toe slides off nosing or foot misses tread completely)
- overstep (toe locks against nosing)
- structural collapse of the step
- unintentional use of the steps, unaware of presence of step(s)

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TABLE 1.4
Stair Falls and Gait

Direction	*Slips*	*Missteps*	*Stumbles*	*Balance Loss*	*Other*	*Total*
Up	*12 (23)*	*9 (17)*	*18 (33)*	*9 (17)*	*5 (9)*	*53*
Down	*70 (40)*	*57 (33)*	*21 (12)*	*13 (8)*	*12 (7)*	*173*
Total	*82 (36)*	*66 (29)*	*39 (17)*	*22 (10)*	*17 (8)*	*226*

Note: Figures in parentheses show the percentages by row.
Source: Svanstrom (1973).

BALANCE LOSS DURING DESCENT:
- catch heel on nosing
- catch toe on nosing strip
- overstep (foot slides off nosing or misses the step completely)
- Understep (heel locks against riser)
- structural collapse of the step
- unintentional use of the step, unaware of presence of step(s)

Few studies have attempted to isolate the gait incidents that result in a fall on a stair. Svanstrom's (1973) findings are useful because they differentiate between falls in ascent and descent. Table 1.4 was derived from the victims' own memories and descriptions of the events. Unfortunately, most incidents occur so quickly and unexpectedly that the victim often does not know or remember precisely what went wrong. For this reason, "slipped," as a cause, should be treated cautiously. A slip is a relatively unlikely event, and it is quite likely that "slipped" is the only explanation that the victim can think of to explain what happened. It also psychologically transfers the blame to the stair.

What can we conclude from this? What are the most prevalent gait failures? How can we minimize them?

1.7 WHAT TYPES OF FALL OCCUR?

Few records describe the types of fall that occur. In Svanstrom's study, approximately 50 percent of the victims fell forward on the stairs, 40 percent fell backward, and 10 percent fell sideways. He did not indicate whether this distribution holds true for ascent as well as descent or whether, as one might suspect, the distribution for ascent is quite different.

In a fall, there are four significant components of motion:

- rotation—either forward or backward—about the center of gravity
- horizontal translation of the center of gravity (forward or backward)
- vertical translation of the center of gravity (up or down)
- lateral translation of the center of gravity (to the left or right)

Obviously the kinematics of the fall depend on its cause and other factors. There have been few attempts to describe or model stair fall kinematics.[3] Maki (1983, 4–7) proposed a fixed-axis rotational model and a general model of stairway falls. Neither model, however, includes lateral translation, which probably is important in no more than 10 percent of falls.

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The fixed-axis rotational model (fig. 1.4) treats the human body as an inverted pendulum, rotating (and falling) about the supporting foot. This is the case when most of the body's weight is being carried on the one foot (during the swing phase) and there is little hip and knee rotation. The step, or the landing, provides the reaction moment, transmitted through the foot to the body. However, the rotational moment of the body will carry the body to the ground unless it can be counteracted by the victim's grabbing the handrail or taking some other stabilizing action.

When the weight is distributed between the two feet (heel down, stance, and toe-off phases) at the outset of the fall and after substantial hip and knee rotation has occurred, the fixed-axis rotation model becomes inadequate. Now the center of gravity may be translated forward, backward, and downward. The ground reaction force will limit the downward acceleration (due to gravity), unless the knees buckle under the load. Maki's general model (fig. 1.5) illustrates the forces.

1.8 Why Is It Difficult to Avoid Falls?

Generally people have difficulty regaining their balance before an incident turns into a fall because there is insufficient time. Jones and Watt (1971, 729–737), in their studies of sudden falls, deal with three phases or reactions: the reflex answer, the answer of will, and the functional stretching reflex. The reflex answer is the automatic reaction to the sense that a fall has started; 102 milliseconds after the fall is sensed, regardless of whether one has landed, the gastrocnemius muscle (the large muscle at the back of the lower leg that extends the foot and assists in flexing the knee) starts to contract. During the time taken for the reflex to start and the muscular contraction to build up, the body or limb falls about 2 inches (5 cm). Therefore, after falls of 2 inches (5 cm) or less, one lands completely unretarded by muscular effect, and with an unpleasant jolt.

After a fall starts, more than about 190 milliseconds is needed for an answer of the will to occur so a well-controlled landing can take place. During this time, a fall of about 7 inches (18 cm) will have taken place. Because most steps are less than this, there is not enough time for a controlled landing if, for example, one encounters a step that one does not know is there.

The functional stretching reflex needed to soften an unexpected fall, according to Jones, starts much too late after one has landed—170 milliseconds—to be able to soften an unexpected fall. From this, Svanstrom concludes, "If one lands from a fall of 30 cm (11.8 inches), then the point [center] of gravity will fall a further 50 cm (19.7 inches) before the thigh muscles of the person even start to be influenced by this reflex, starting an effective contraction." Svanstrom then speculates, "This might be the explanation to the remarkable injuries which may be caused by short, unexpected falls, and that the injuries caused by such falls do not only depend on how far one falls."

This, then, is the disadvantage one suffers on a stair: our natural defensive reaction system will not help much until after we have already fallen about one step of 7 inches (18 cm). By this time, we may be completely off balance and trying frantically to find a place for our feet and support for our body. This desperate search for support is not always successful, and

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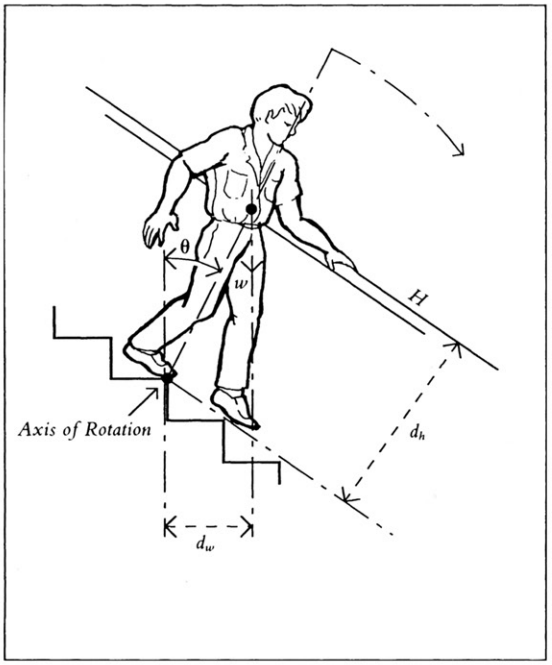
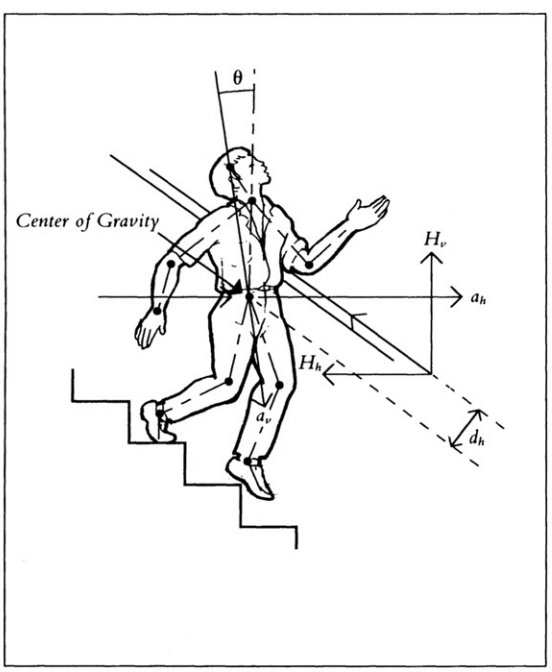


1.4 *Maki's fixed-axis rotation model of stairway falls*

θ = *angle of inclination of inverted pendulum*
W = *body weight*
H = *handrail force*
d_w = *moment arm of body weight*
d_h = *moment arm of handrail force*
Note:
destabilizing torque = $W \times d_h$



1.5 *Maki's general model of stairway falls*

θ = *angular acceleration about center of gravity*
H = *handrail force*
H_h = *horizontal component of handrail force*
H_v = *vertical component of handrail force*
a_h = *horizontal component of acceleration of center of gravity*
a_v = *vertical component of acceleration of center of gravity*
d_h = *moment arm of handrail force*
Note:
H_h *opposes horizontal acceleration* (a_h)
H_v *opposes vertical acceleration* (a_h)
stabilizing torque $H \times d_h$ *opposes angular acceleration about center of gravity*

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the fall may continue. Nevertheless, the search for support takes place and may be successful if there are handrails or if the fall can be controlled in some other fashion.

1.9 What Injuries Result from Falls on Stairs?

The most useful studies of stair accident injuries are those, discussed by Svanstrom (1973), that were conducted in Copenhagen (1953), Odense (1971), and Malmö (1973). Svanstrom concluded that there is substantial agreement in the findings of the three studies. Tables 1.5 and 1.6 show some of the findings of Svanstrom's own study in Malmö. The largest single category of injuries (36 percent) was of head injuries. The proportion of head injuries was even larger for young people under 20, for whom 58 percent of all injuries received were head injuries. Why this should be so is not clear, nor is why young people had so few trunk injuries. We might speculate that this is because children's heads are disproportionately large and supported by a weaker neck structure and that, being small, children have less time to protect their heads when they fall. Perhaps all that we can conclude is that children's heads are particularly vulnerable in stair accidents (as well as in free-fall and automobile accidents) (Snyder 1964, 136–164) and that the injuries are caused by striking the steps, balustrade, or handrail. For older age groups, injuries to the head were no more frequent than injuries to the feet, the next largest category. Also, if we combine the lower extremity and foot injury categories, these account for almost half (44 percent) of all injuries, for ages 20 and older. In view of our gait on stairs, this is perhaps not unexpected.

A closer examination of Svanstrom's study shows that all the fractures of lower extremities, excluding feet, occurred during descent. All of these injuries were caused by a twisting of the lower extremities. In fact, 75 percent of all injuries to feet and ankles occurred in descent, and 86 percent of those who fractured their lower extremities fell forward. These injury patterns are consistent with what might be expected from falling forward onto a leg or a foot while descending. Significantly, 71 percent of those with fractures to the lower extremities were over 70 years old, and 57 percent of all those injured by blows to the lower extremities were over 50, illustrating the vulnerability of older groups to more severe injuries after falls.

Only 19 percent of all the injuries affected the upper extremities (arms and hands). A larger proportion of upper extremity fractures (39 percent) than of lower extremity fractures (22 percent) occurred during ascent, probably reflecting the natural defense of using arms to prevent one's trunk and head from striking the steps during a fall in ascent. And from the data, 72 percent of all fractures and 86 percent of all upper extremity twisting injuries occurred while falling forward—presumably while using the arms to try to limit the extent of the fall. Again, age was a significant factor in the injuries: 74 percent of the people with upper extremity fractures were over 40.

Only 8 percent of the victims injured their trunk. All who suffered fractures to the bones of the chest, trunk, and pelvis were over 50 and were descending the stairs. Eighty percent of injuries to the trunk occurred after falling backward. These data suggest a pattern of injuries re-

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TABLE 1.5

Stair Accident Injuries by Type and Age of Victim

	Age of Victim				
Injury Location	*0–19*	*20–39*	*40–59*	*60+*	*Total*
Head	36 (58)	14 (33)	9 (20)	13 (27)	72 (36)
Trunk	1 (2)	5 (12)	6 (13)	4 (8)	16 (8)
Upper extremities	11 (18)	5 (12)	13 (29)	8 (16)	37 (19)
Lower extremities, except feet	4 (7)	4 (9)	7 (16)	14 (29)	29 (15)
Feet	10 (16)	15 (35)	10 (22)	10 (20)	45 (23)
Total	62 (31)	43 (22)	45 (23)	49 (25)	199 (100)

Note: the figures in parentheses give the percentages for the column they are in, except that the figures in parentheses in the bottom row give the percentages for this row.

Source: Svanstrom (1973).

TABLE 1.6

Injuries and Parts of the Body Affected

	Part of Body Injured					
Injury	*Head*	*Trunk*	*Upper Extremity*	*Lower Extremity*	*Feet*	*Total*
Fracture	2	4	19	7	12	44 (22)
Concussion	34					34 (17)
Wounds	29		1	6		36 (18)
Blow/crushing	8	12	10	14	3	47 (24)
Twisting			7	2	30	39 (20)
Total	73 (37)	16 (8)	37 (19)	29 (15)	45 (23)	200

Note: figures in parentheses give percentages by row or column.

Source: Svanstrom (1973).

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sulting predominantly from the type of fall where, in descent, the victims lost their footing through a misstep or overstep and fell backward. Summarizing the patterns of injuries and accidents, we find that

- falling forward in descent is likely to injure the upper and/or lower extremities
- falling forward in ascent is likely to injure the upper extremities
- falling backward in descent is likely to injure the trunk
- children are likely to injure their heads
- older people are more likely to receive fractures

1.10 How Are Injuries Caused?

We can only speculate as to how stair injuries are caused, because none of the studies has discussed the relationship between stairs as constructed and the types of injuries that might be caused when someone falls. However, there are clues.

Ninety percent of the victims fell forward or backward onto the stair, so the steps themselves were more than likely the instrument of injury in most cases, and probably most of the steps were of concrete, wood, steel, or similar materials, although some may have been carpeted. The steps, therefore, were as hard a place on which to fall as a concrete, wood, or steel floor—providing nothing to absorb the force of the fall or the impact of any blow. The surface of some of the steps may, in fact, have been as welcoming as a cheese grater and just as effective for tearing flesh from bone (fig. 1.6).

If the steps provided an even surface like that of a floor on which to fall, the fall would be less injurious. In a stair fall, however, it is often impossible to avoid falling against one or more of the step nosings. At best, these have a rounded corner edge and, at worst, a sharp corner edge.

In 10 percent of the falls in Svanstrom's study, the victim fell sideways and presumably fell against the handrail, balustrades, stringer, or sidewalls. A cursory inspection of most handrails, balustrades, and stringers is not very reassuring; many have sharp edges and even sharp points against which to fall (fig. 1.7).

Without more detailed information about accidents, we can only speculate about what actually causes the damage. Nevertheless, we can make reasonable guesses. For example, it seems likely that most of the fractures and concussions (mostly to children) were caused by the head striking the steps or landing, or perhaps in a few instances adjoining walls, but probably not handrails or balustrades. On the other hand, the wound injuries to the head may well have been caused by the sharp edge of nosings and balustrades.

Most of the twisting injuries occurred during descent, and it is likely that most of these occurred as the leading foot dropped awkwardly onto a step. Twisting and fractures of the upper extremities are most likely to have occurred as the victim, in falling forward in ascent or descent, put out an arm toward the step (or the handrail) to abort the full impact of the fall.

Fractures of the feet and leg occurred during descent, usually while falling forward (and this is unlikely to be head over heels), so probably the victim fell heavily onto one or more steps or the landing, with one foot or leg bearing the brunt of the accident.

Fractures and crushing or blows to the trunk occurred usually when the victim fell

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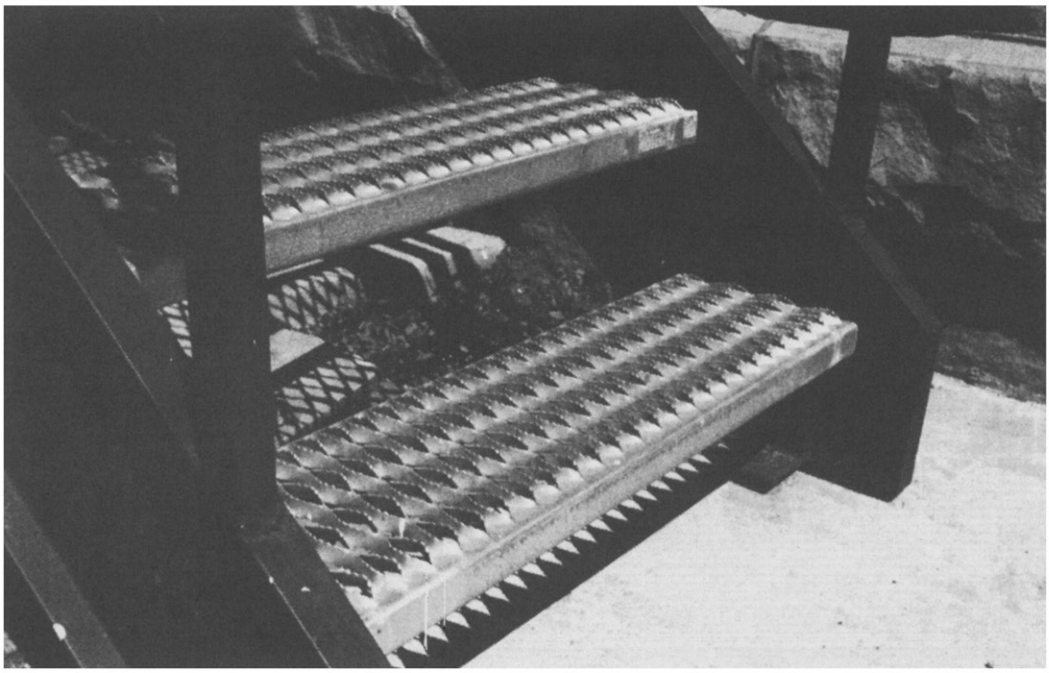
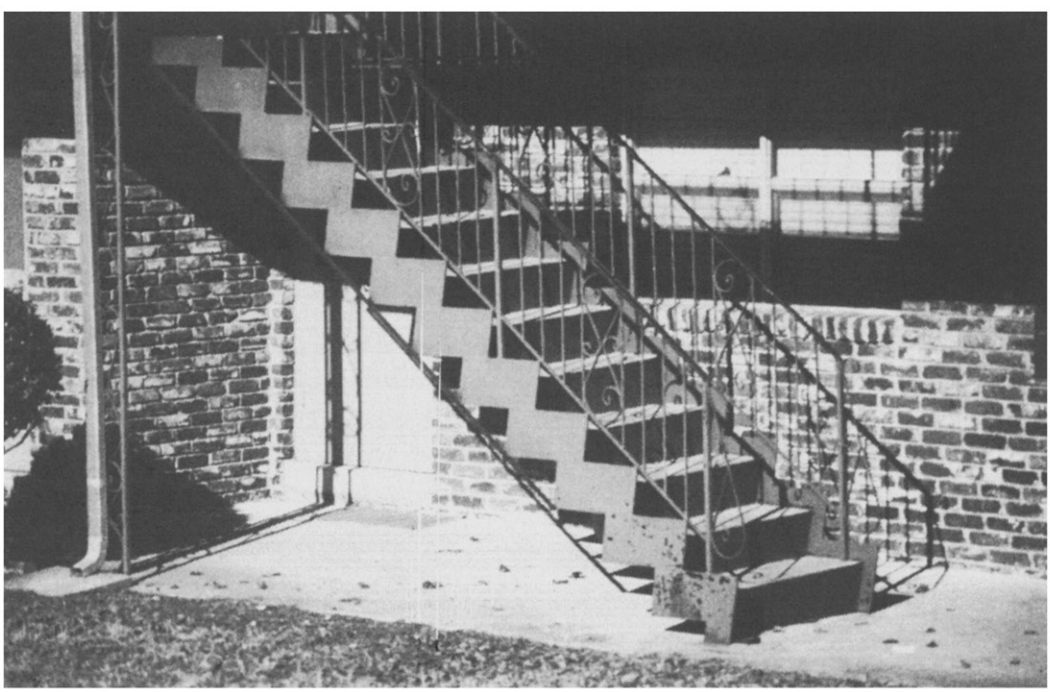


1.6 *The cheese grater tread*



1.7 *Steel stair*

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backward onto the steps while descending the stair. Presumably the nosing edge inflicted most of the damage.

The remaining injuries—wounds, blows, crushing—inflicted on the upper and lower extremities are likely to have occurred as a result of forcible contact with the sharp edges of nosings, balustrades, and handrails.

Based on this conjectural injury analysis, we can construct a table using Svanstrom's data to establish, roughly, those components of the stairs that are responsible for most injuries (table 1.7). The hard surfaces of steps and landings account for the bulk of the injuries; however, the nosing edges account for nearly a third and handrails, balustrades, and adjoining walls the remaining 13 percent. From this, we can conclude that more than 80 percent of all injuries are caused by contact with treads, landings, and/or nosings. The rest are caused by impacts against handrails, balustrades, and adjoining walls. In terms of injuries inflicted, the stair of today is not different from that of five thousand years ago. A fall down the stairs is comparable to falling into a hole with jagged rocks at the bottom.

1.11 What Influences the Severity of Injuries?

Several factors during a fall influence the nature and severity of any injury; no single factor is of primary importance. Those who have studied injuries incurred during automobile accidents or free-fall accidents (falls from airplanes, bridges, windows) report that the following conditions affect injuries (Snyder 1963, 1977): orientation of the body, magnitude of the force, duration of the force, and characteristics of the impacted surfaces.

1.11.1 Orientation of the Body

The location of the impact point on the body is significant. A fall onto the top of the head may result in an impact force per square inch of body surface that is the same as that from a fall onto the feet. There is, however, a difference between the ability of the skull and the leg structures to absorb the blow, and, obviously, brain injury is potentially more serious than damage to the feet and legs. Second, if in the fall the impact is distributed over more of the surface of the body, the force of the blow at any particular point is diminished. Falling against an edge or a

Table 1.7

Stair Elements and the Parts of the Body That They Injure

	Part of Body Injured					
Stair Element	*Head*	*Trunk*	*Upper Extremity*	*Lower Extremity*	*Feet*	*Total*
Steps, landing	*36*		*23*	*19*	*40*	*118 (59)*
Nosings	*24*	*13*	*8*	*8*	*3*	*56 (28)*
Handrails, balustrades	*13*	*3*	*6*	*2*	*2*	*26 (13)*
Total	*73*	*16*	*37*	*29*	*45*	*200*

Note: figures in parentheses represent percentages by column.

Source: adapted from Svanstrom (1973).

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sharp point, for example, is more likely to cause injuries than falling on a flat surface. In the former case, the full force of the impact is concentrated onto a small area.

1.11.2 Magnitude of the Force

The pressure developed in the body during an impact is dependent on the magnitude of the force of the blow and the surface area of the body that is struck. In a fall, the impact force is dependent on the victim's weight (mass), the velocity of the body at the time of the impact, and the extent to which the body and the object that it strikes deform. Not a great deal is known about the distance of deformation of the tissues of the body under various circumstances. Therefore, impact tolerance data are based on estimates.

1.11.3 Duration of the Force

The duration of the force is the time required to reach the peak force at the initial impact. As Snyder (1963) has noted, "This may approach zero when impacts against non-yielding rock or concrete surfaces are encountered." In general, the greater the time duration, the less the injury, and the time duration is dependent on the impacted surfaces.

1.11.4 Characteristics of the Impacted Surfaces

The object or surface that is struck will have elastic and contour characteristics, which will affect deformation and time duration, respectively. As one would suspect, falling onto soil would reduce peak acceleration and normal forces to about one-third to one-half of those present in falls onto rigid materials such as concrete. A fall onto soft sand might result in values of only 15 to 22 percent of rigid surface values.

Similarly, the body's tissues differ in elasticity, viscosity, tensile and shearing strength, and compressibility. An impact force against bone produces little or no displacement until the bone fractures when the yield point is reached. A blow to the gluteus maximus that might be largely dissipated by the elasticity of the tissues might have severe consequences if it falls onto the skull.

The contour or shape of the impacted surface is obviously significant. For example, a fall against the square edge of a nosing projection (or the sharp edge of a rail or a baluster) is likely to be much more traumatic than a fall against a flat surface such as a landing.

An understanding of the forces involved in stair injuries can help us to control these forces. We have seen that the forces that come into play during stair accidents can be calculated approximately. An examination of these forces explains why injuries from stair accidents are so often serious. Moreover, the materials that people fall onto or against, and the shape of handrails, nosings, balusters, and so on, can make the difference between a fatal accident or a relatively minor injury.

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2 Riser and Tread Geometry for Comfort and Safety

Once I tried to make a standardization of staircases. Probably that is one of the oldest of the standardizations. Of course, we design new staircase steps every day . . . we tried to solve the matter by an elastic system. . . . For the movement of the human being there is a special rhythmical form. You can't make a step how you like; it must be a special proportion. I spoke about that in the University at Gothenburg. The Rector . . . came out with a book—Dante's Divine Comedy. *He opened it at the page where it says that the worst thing in the inferno is that the stairs had the wrong proportion. (Aalto 1957)*

2.1 Stair Geometry in History and Theory

This theorem [Pythagoras's] affords a useful means of measuring many things, and it is particularly serviceable in the building of staircases in buildings, so that the steps may be at the proper levels. Suppose the height of the story, from the flooring above to the ground below, to be divided into three parts. Five of these will give the right length for the stringers of the stairway. Let four parts, each equal to one of the three composing the height between the upper story and the ground, be set off from the perpendicular and there fix the lower ends of the stringers. In this manner the steps and the stairway itself will be properly placed. (Vitruvius 1926, 253)

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With this description, Vitruvius in the first century B.C. set down the earliest known design guideline for stair layout. Ever since (and almost certainly before), the quest for the perfect relationship of riser to going, and stair pitch, has been a kind of designer's philosopher's stone. Almost every architect of note for the last two thousand years has held decided and often differing views on the proper geometry of stairs for comfort and safety.

Vitruvius is unlikely to have derived his theoretical material himself. We must assume that his views to a large extent reflected the prevailing practice. His books are dedicated to Caesar, and his clients must have been patrician. So the quite gentle pitch of 37 degrees that he proposes would reflect, from his professional experience, what these patrons would accept and expect. He recognizes that monumental buildings may require these recommendations to be modified, so for temples he writes, "The rise of such steps [for a temple] should, I think, be limited to not more than ten nor less than nine inches [22.8–25.4 cm]; for then the ascent will not be difficult. The treads of the step ought to be made not less than a foot and a half [45.7 cm], and not more than two feet deep [61 cm]" (Vitruvius 1926, 88).

Alberti (1986, 19), writing about fifteen centuries later in the first printed book on architecture, noted that the Romans and Greeks never made steps higher than 9 inches (22.9 cm) or lower than 5 inches (12.7 cm) and goings less than a foot and a half (45.7 cm) or more than a yard (91.4 cm). His facts were incorrect. Risers of 10 to 12 inches (25–30 cm) were not uncommon in Herculaneum and Pompeii, for example. However, Alberti's approach was to try to define limits for risers and goings, in much the same way that many building codes do today. If imperial Rome was his inspiration, it is likely that it was his experience of and reaction to the austerity and severity of medieval stairs that helped define his limits, particularly the generous going dimensions he advocated. The dawn of the stair as a ceremonial and dignified focus was soon to occur.

By 1570, the life-style of the rich and noble demanded proportions in keeping with the stair's new importance as a ceremonial setting, so the limits were drawn much closer than Alberti's proposals and made more generous, and for the first time, a simple physiological justification was offered. "The steps," writes Palladio (1965, 34), "ought not to exceed six inches in height [6 Vicentine inches of the time would equal 6.8 English inches (17.3 cm) of today] and if they be lower, they must chiefly be in long and continuous stairs, for they will be so much the easier because one needs not to lift the foot so high; but must never be lower than four inches [4.5 inches today, 11.4 cm]. The breadth of all steps ought not to be less than one foot [30.5 cm] nor more than one and a half [45.7 cm]."

Palladio's influence as a designer and theorist was widespread. One of the first men to carry his ideas to England was Sir Henry Wotton (1568–1639). Wotton was royal ambassador to Venice, and according to Marwick (1888, 116) he was acquainted with Palladio. Certainly his *Ground-rules of Architecture Collected from the Best Authors and Examples,* published posthumously in 1686, leans heavily on Palladio's *Four Books*

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of Architecture. But Wotton (1686) adds some important observations not touched on by Palladio:

To make a complete stair-case is a curious piece of Architecture; the vulgar cautions are these. That it have liberal light against all casualties of slips and falls. That the space above the head be large and airy because a man doth spend much breadth in breathing. That the half paces be well distributed at competent distances for reposing on the way. That to avoid Encounters, and besides to gratifie the beholder, the whole stair-case have no niggard latitude, that is for the principal Ascent in Royal Buildings at least ten foot. That the breadth of every single step or stair be never less than one foot, nor more than eighteen inches [45.7 cm]. That they exceed by no means half a foot [15.3 cm] in their height or thickness, for our legs do labour more in elevation than in distention. That the steps be laid where they join somewhat sloping that the foot may in a sort ascend and descend together; which though observed by few, is a secret and delicate deception of the pains in mounting.

This secret deception, the "wash" or "kilt," was a feature of stairways in the high Renaissance and baroque. However, it is seldom mentioned by other writers and almost never since the beginning of the twentieth century. In fact, its use has almost disappeared in modern stair design. Except as a device to throw water off external stairs, it is never mentioned in any of the current design handbooks. This is interesting as, from experience rather than fashion, the architects of the golden age of stair design obviously considered that this refinement made stair climbing less taxing, and it was used ubiquitously.

By the end of the seventeenth century, current attitudes, in England at least, demanded even gentler slopes. We find John Evelyn writing in 1686 that risers should "not exceed five inches in height [12.7 cm], or be less than fifteen in breadth [38.1 cm], one foot [30.5 cm] being scarcely tolerable." However, it was in France in the late seventeenth century that the first known attempt was made to devise a formula that linked stair geometry to human gait. François Blondel, who became director of the Royal Academy of Architecture in 1672, was the author of the influential *Cours d'Architecture*. Blondel (1675) noted that "the length of a comfortable pace of a man who walks on the level is . . . twenty-four inches. And the [maximum comfortable] height of one climbing a vertical step is only twelve inches." He concluded that for every inch of height for the riser, one must subtract 2 inches from the pace, or expressed mathematically,

$$2 \times \text{riser} + \text{going} = 24 \text{ in.}$$

Blondel probably referred to the French (pre-Revolutionary) royal inch, the equivalent to 1.0568 inches in today's measure.[1] Blondel's 24 inches was therefore equivalent to 25½ inches (64.77 cm) by today's measures. If we adjust for the pace of people today, depending on leg length and walking speed—say, 28 inches (71 cm)—and express the formula in today's measures, then it would become:

$$2 \times \text{riser} + \text{going} = 28 \text{ in. (71 cm).}$$

This would generate much larger treads than are common today. Five-inch (12.7 cm) risers would be paired with 18-inch (45.7 cm) treads; 6-inch with 16-inch (15.2 with 40.6 cm); 7-inch with 14-inch (17.8 with 35.6 cm); and 8-inch with 12-inch (20.3 with 30.5 cm).

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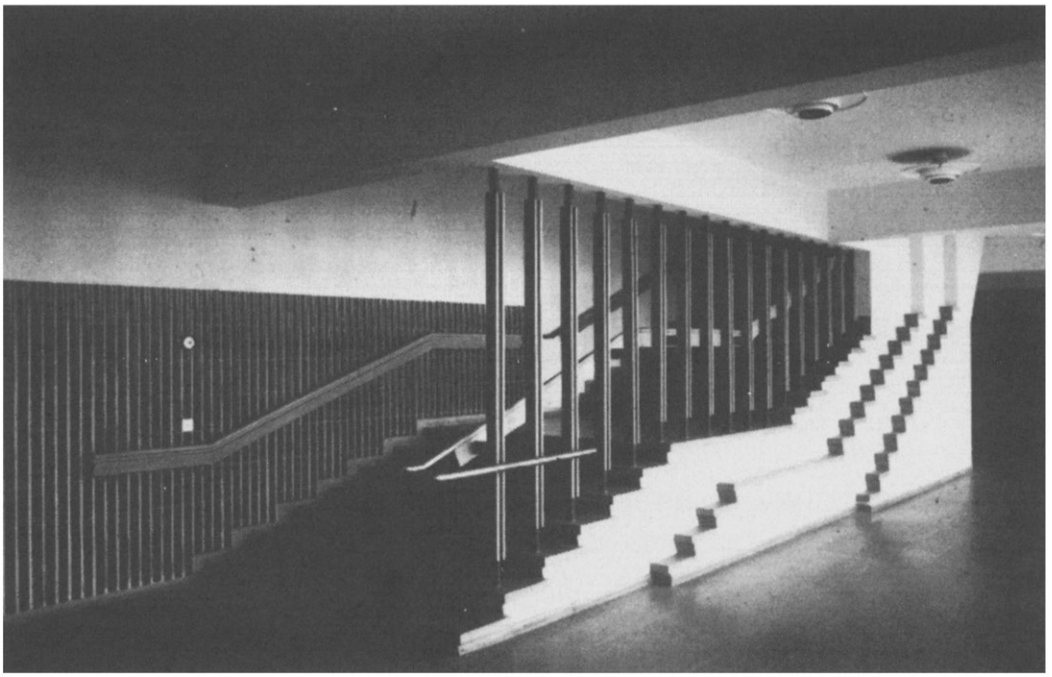

2.1 *Aalto's stair, showing three stair ratios*

The clarity of Blondel's thesis recommended this formula to architects everywhere, and it was widely adopted. It might be something of a surprise to Blondel to find that three hundred years later his (now incorrect) formula, under several national building codes, controls what may and may not be built. Blondel's empirical anthropometric tenets have taken on the force of law in the twentieth century—without adaptation to allow for changes in mensuration and human dimensions.

Inspired by Blondel's scientific-sounding formula, many competitors and modifications have appeared over the years, for example:

$R + G = 17$ in. (43.2 cm)
$R \times G = 75$ in. (190.5 cm)
$R/G = \tan [8\ (R - 3)]^\circ$

and a matching pair, when G, the going, is fixed:

$$R = 9 - \sqrt{7(G - 8)(G - 2)}$$

or when R is fixed:

$$G = 5 + \sqrt{1/7(9 - R)^2 + 9}$$

A drawback to the Blondel rule was perceived by the critics. Where the risers are higher or lower than usual, the rule produces extremely narrow or extremely wide treads.

The source of the first three equations is obscure.[2] The latter two were presented by Ernest Irving Freeze in the July 1933 and March 1934 issues of the *American Architect*.[3] His research method is not revealed, however. "The theoretical analysis that

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eventually led to the discovery of the 'hyperbolic variation of tread and riser,' " he says, "is of no consequence."

2.2 Personal Preference

2.2.1 Olmsted's Curves

One of the most interesting discussions and examination of these formulas was written by Frederick Law Olmsted and published in 1911.[4] It could even have been the observational source of Freeze's formulas. Over a period of about nine years, Olmsted conducted a personal program of stair evaluation in which he systematically recorded the sizes of risers and treads of steps that he encountered and whether they "seemed distinctly too large or too small or reasonably satisfactory for the given rate of slope of that particular flight." He supplemented his own subjective experiences by asking companions to pass judgment also. Olmsted's graphical presentation of the results and his curve of optimum step sizes (fitted by eye) are shown in fig. 2.2. In this diagram, to indicate unsatisfactory ratios, he uses the simple expedient of showing an arrow from the data pointing in the direction to which it should be altered to improve it. Figure 2.3 shows the curve that Olmsted recommended for risers of 7 inches (17.8 cm) and more—his rule 1—and his second curve for risers that are less than 7 inches (17.8 cm)—his rule 2. On the same graph, he plots the lines of other formulas and the sources to which he attributes them. It is worth noting that Olmsted always included a wash of ¼ inch to 1 foot (1:48) in his recommendations.

2.2.2 Laboratory Exploration

Personal preference has also been explored in the laboratory by Ward and Randall (1967, 29–34). They asked forty subjects, twenty men and twenty women aged between 62 and 79, to ascend and descend twelve riser-tread combinations—risers of 7, 8, and 9 inches (17.8, 20.3, and 22.9 cm) combined with treads of 8½, 10½, and 11½ inches (21.6, 26.7, and 29.2 cm). They were then required to rank them in order of preference in terms of ease, safety, and comfort. For each of the four treads, both men and women preferred 7-inch risers to 8-inch (17.8 to 20.3 cm), and 8-inch risers to 9-inch (20.3 to 22.9 cm).

In another study, Ward and Beadling (1970, 513–519) reported the results of asking twelve men and twelve women aged 20 to over 40 to rank three stairs in terms of ease and comfort. Stair A had 7.87-inch (20 cm) risers and 8.54-inch (21.7 cm) treads; stair B had 8.54-inch (21.7 cm) risers and 10.04-inch (25.5 cm) treads; stair C had 9.23-inch (23.4 cm) risers and 11.02-inch (28 cm) treads. Once again the lowest riser was preferred as first choice; however, the investigators reported that "many subjects found it extremely difficult to make any distinction at all, and others said they would have given a clear first choice to a combination of the riser of stair A for ease of ascent and the going of stair B for ease of descent."

Neither of these two studies is altogether satisfactory. In the first study, there is an obvious age bias. Furthermore, the subjects climbed to the beat of a metronome at a fixed, constant rate. This forced them to climb at a faster rate of vertical ascent when climbing the higher risers than when climbing the lower risers. The result was that they were expending energy at a faster rate for the higher risers. In the second study, the range of stairs used was very

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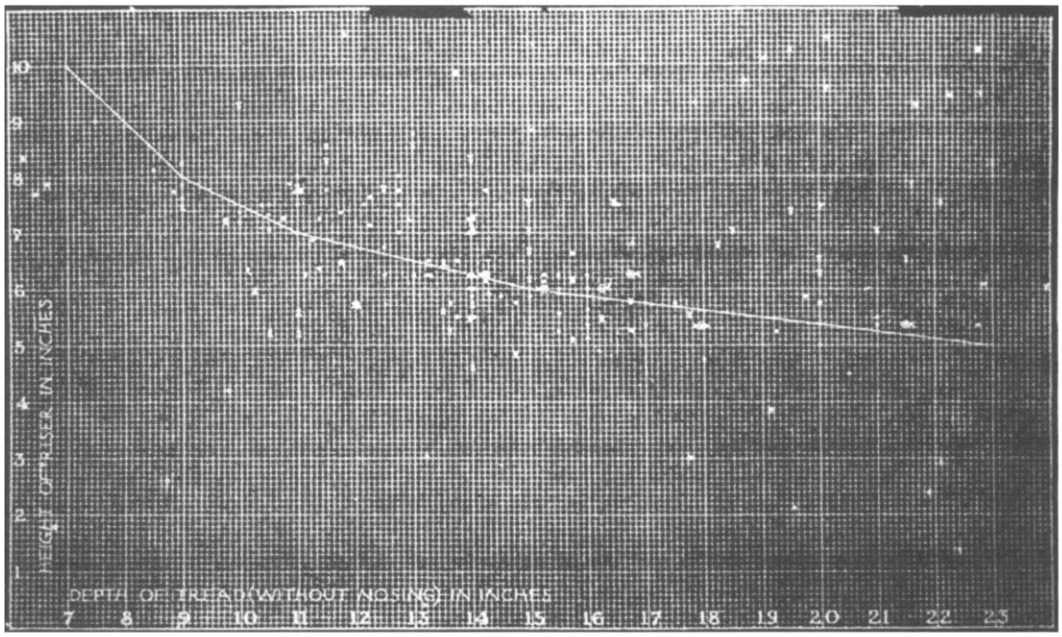
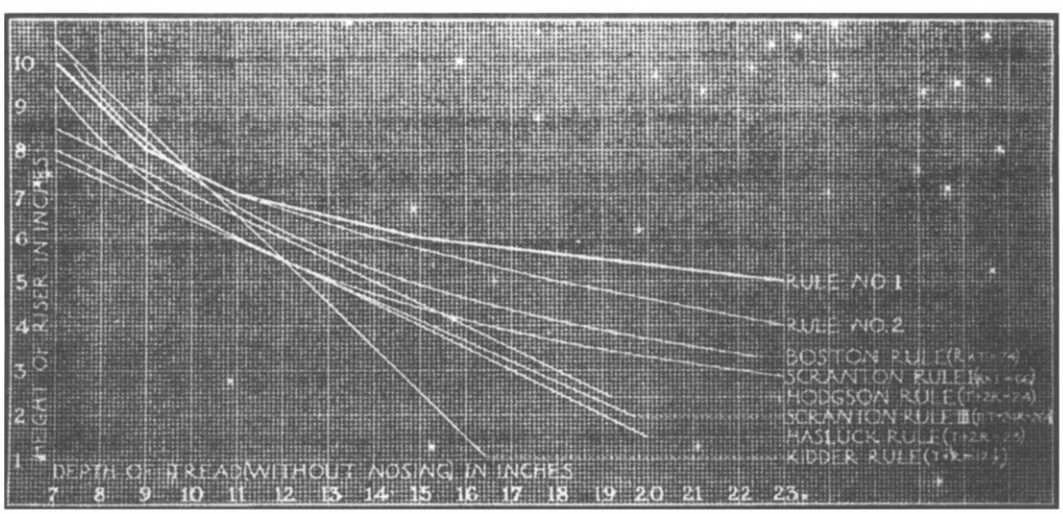


2.2 *Olmsted's optimal step sizes*


HEIGHT OF RISER IN INCHES
DEPTH OF TREAD (WITHOUT NOSING) IN INCHES
7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
RULE NO. 1
RULE NO. 2
BOSTON RULE
SCRANTON RULE
HODGSON RULE
SCRANTON RULE
HASLUCK RULE
KIDDER RULE

2.3 *Olmsted's and other rules*

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limited and the risers were unusually high. With these reservations, however, both studies did agree that, in the range of risers from 7 to 9½ inches (17.8–24.1 cm), when used in combination with goings ranging from 8½ to 11½ inches (21.6–29.2 cm), the lower the riser was, the more highly it was preferred.

2.3 Human Energy Expenditure and Riser-Tread Combinations

Soon after World War I, a quite new and more rigorous approach to stair research began. Researchers sought to compare the energy demands on the human metabolism of different riser-tread combinations to see whether some were easier to climb than others. The most influential of these studies was by Lehmann and Englemann (1933, 271–282), who concluded that risers should be 17 cm (6.7 inches) high, with 29-cm (11.4 inch) goings. If it is necessary to deviate from this optimum, they suggested that the stair should follow the formula:

Going − Riser = 12 cm (4.7 in.).

Their conclusions are still influential in European design data books (Shuster 1970, 8; Aloi 1973, 21). However, their study was limited by the techniques then available, and the researchers made their subjects climb at a constant stepping rate regardless of the riser-tread combination, a decision that is questionable.

Energy expenditure as a measure of rhythm, comfort, and fatigue seems to offer one of the most productive approaches to the development of stair geometry criteria. In terms of energy expenditure, human bipedal posture is extraordinarily efficient for traversing long distances economically. Sherwood L. Washburn (1960) has suggested that it was human walking, as a variant from the quadrupedal mode, that enabled people to exploit a far wider range of environments than other anthropoids whose gaits were well adapted to but also limited to tropical forests and woodland savanna.

It has been estimated that more than 20 percent of everyday human muscular energy is spent in walking (Simeon 1971, 1). As a combustion engine, the human body is careful to conserve its energies, and this is reflected in its walking habits. The rate of expenditure of energy during walking increases sharply as the pace is quickened, but the total energy expended in going from place to place does not match this increase. The total energy cost of walking a mile, say, is much greater at 1 mile an hour (and also at 6 miles an hour) than it is at 3 miles an hour (Corcoran 1972, 192). And several studies have shown that people spontaneously select speeds close to the latter as a usual unhurried walking speed.

At 3 miles an hour, the rate of expenditure of energy is maintained below 5 kilocalories per minute. Five Kcals per minute is about the maximum rate of expenditure that most people can maintain for long periods without a rise in the serum lactic acid level—without incurring the so-called (incorrectly) oxygen debt (Corcoran 1971, 188). In terms of energy expenditure, then, human gait operates optimally not at very low rates of energy expenditure but at a rate that will enable people to travel long distances with the least total effort.

The rhythm of walking is normally regular and even. Any conditions that disturb this natural movement are reflected in the energy expenditure patterns. A tight dress increases the energy used. Three-inch (7.6 cm) high heels may cause a 10 to 15 per-

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cent increase—more than that produced by having both ankles immobilized in a cast (Corcoran 1972, 194). And walking on soft or uneven ground may increase energy demands by 40 percent or more.

2.3.1 Previous Studies

Human metabolic patterns have been studied on the premise that some stair geometries may generate rhythms congruent or incongruent with human gait and that these would be reflected in changes in energy expenditure; it has been suggested that certain combinations of riser, tread, and speed might be better suited to human gait and therefore demand less effort from the human body than other combinations.

The early attempts at measuring the metabolic cost of stair climbing were carried out soon after the end of World War I. The researchers were interested more in the mechanical efficiency of the body than in the effort of climbing stairs. It was not until 1933 that the stair itself became the focus of experimentation. Lehmann and Englemann's studies at the Max Planck Institute in that year were the first directed specifically at measuring the energy demands of a range of stairs under controlled laboratory conditions, and their findings were very influential on European stair design.

2.3.2 Shortcomings of Earlier Studies

Neither Lehmann and Englemann's study nor subsequent studies by Keiser (1958) and Richardson (1966, 1078–1082) were wholly satisfactory. None of these studies adequately resolved the relationship between rate of vertical ascent and energy expenditure. Their subjects climbed the stairs (or stair treadmill in the case of Richardson) at a fixed step rate as regulated by a metronome (or the treadmill motor). Therefore, when the riser height was increased, the rate of vertical ascent increased simultaneously. Rate of ascent was shown in a study by Benedict and Parmenter (1928, 675–698) to affect energy expenditure significantly. This was confirmed by the studies made by Templer and Corcoran (1972, 67–86) at the New York State Rehabilitation Hospital at West Haverstraw. Rate of ascent, then, cannot be ignored without jeopardizing the results. Furthermore, observations of stair use have shown, as one might suspect, that a person's normal rate of climb is related to the riser-tread ratio of the stair.

The metabolic research carried out at Haverstraw tried to remedy these conceptual difficulties (fig. 2.4). The aim of the study was to establish whether there is a predictable and constant relationship in terms of the affective parameters. The primary aim was not so much concerned with the actual magnitude of oxygen consumption (useful as this would be for physiological purposes) as with obtaining figures that would demonstrate the comparative rates of consumption per unit time and distance for the various experimental setups, for this would answer the question whether there is an ideal riser-tread ratio, or range of ratios, that is significantly less demanding than others.

A further aim was to compare the energy costs of walking on the level, on ramps, and on stairs. There are usually persuasive reasons for choosing a ramp instead of a stair, or vice versa, in design situations. Nevertheless, there are many locations where each has advantages and disadvantages and the choice is less clear-cut. It would be useful to know the relative energy demands of the alternatives.

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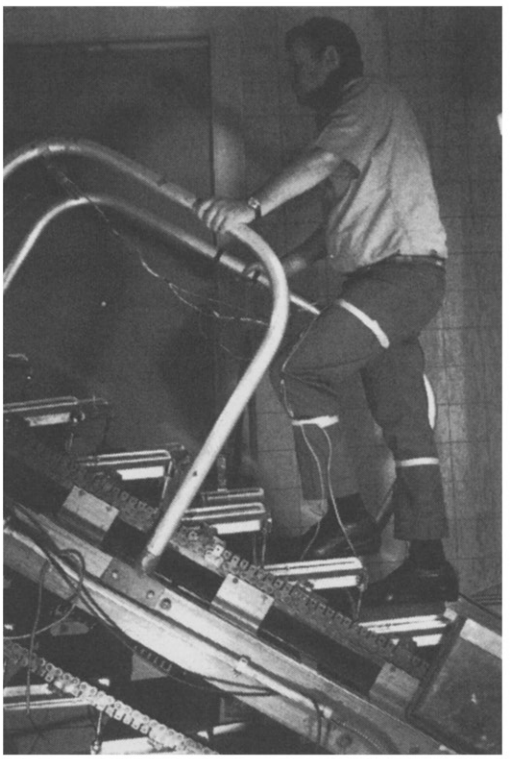

2.4 The stair treadmill used in the Haverstraw study

Tests were conducted at the Hospital's metabolic laboratory using an escalator treadmill that could be adjusted from 23 to 45 degrees—somewhat less than the normally accepted range for stairs (17–48 degrees). The size of the risers and treads could be altered, as could the direction of travel and the speed.

2.3.3 Summary of Findings

• Total Energy Cost per Meter Rise:[5] The tests conducted in these experiments indicated that (for a 70 kg person) the total energy cost of ascending a stair varies in response to the stair geometry. The range is from 0.548 Kcals to 1.12 Kcals per meter of height; for descent it is 0.098 Kcals to 0.280 Kcals per meter. The total energy cost (for a 70 kg person) of climbing ramps of various gradients varies from 0.80 Kcals to 3.0 Kcals per meter. For the lower gradients particularly, ramps have a higher energy cost per meter rise than stairs in general use. This is perhaps surprising until we realize that ramps impose much more horizontal travel for each unit of vertical travel than stairs.

• Total energy cost per meter rise at optimal speeds: For stairs, the energy cost per meter rise is not at a minimum at speeds close to those normally used by pedestrians. In this way, stairs differ from level walking and walking on ramps, where the usual walking speeds enable the individual to maintain the total energy expenditure at a minimum.

• Total energy cost of vertical ascent and gradient: The steeper the stair—up to 45 degrees—the smaller is the total energy cost it demands. For ramps, total energy cost per meter rise decreases as the pitch is

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increased. However, once again, this takes no account of horizontal distances traveled.

• Total energy cost for vertical and horizontal travel: For stairs, when climbing about one story—10 feet (3 m)—vertically and traveling up to 31.43 feet (9.6 m) horizontally, the steeper gradients are the least demanding. However, when climbing 10 feet vertically and traveling a total horizontal distance of 200 feet (61 m), ramps with gradients of less than about 15 percent are more economical than any stair, and as the pitch of the ramp decreases, the ramp becomes more economical in terms of total energy cost.

• Rate of expenditure of energy: Stair climbing demands a rate of energy expenditure that is higher than any other routine daily activity and is comparable to physical heavy labor. The rate of energy expenditure is generally greater for higher risers than for the lower ones; however, steep stairs with high risers and small treads demand no more effort than less steep stairs with much lower risers and large treads. Up to about 11 degrees, 20 minutes, ramps (traversed at normal speeds) demand a lower rate of energy expenditure than any stair in general use.

2.3.4 Implications for Design

The results of these examinations of energy expenditure on stairs and ramps tend to confirm the intuitive, theoretical, and experiential attitudes to stairs and ramps that have developed over the last two millennia. Where horizontal travel is as important as vertical, ramps (with a pitch up to about 11 degrees, 20 minutes) are less tiring than any stairs with risers from 5½ to 7½ inches (14–19 cm)—the most commonly used range. The lower the pitch of the ramp is, the less tiring it becomes; gentle ramps generate gait patterns that closely resemble walking on the level, and the human body is particularly well adapted to these conditions.

As ramps increase in pitch, they become progressively more difficult, uncomfortable, and costly in energy expenditure rates per minute. A point is reached at a pitch greater than about 20 percent when it becomes preferable to use stairs. At this point, or wherever ramps are unsuitable, stairs with low risers demand lower rates of energy expenditure than those with high risers; however, one can choose a riser-tread combination from a range of alternatives that all have about the same energy demands. In this range, high risers are paired with small treads and low risers with large treads. Therefore, it is possible to use quite high risers when this is necessary without incurring a greatly increased rate of energy expenditure—if the treads are small. Combinations that demand relatively low rates of energy expenditure recommend themselves for use in public places and where the aged and the frail are potential users.

Where a stair has to serve only the active and healthy, where horizontal travel is not required, and where ramps are not a reasonable alternative, steep stairs offer advantages over less steep alternatives; although they generally lead to high rates of energy expenditure (because of the normal ascent speeds chosen), their total energy demands are the lowest. However, Ward and Beadling's preference studies (1970) suggest that rate of energy expenditure affects people's judgment of stairs more than the total expenditure. Stairs that demand high rates of

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expenditure were those that were least preferred. Because stair climbing at usual speeds demands expenditure rates that are comparable to heavy manual work, this is not surprising.

Stair climbing is less fatiguing in terms of rates of energy expenditure when the steps are low, but the rate is also related to the proportion of riser to tread. These findings provide supportive evidence of the validity of Blondel's theorizing of three centuries ago. High risers with small treads are no more fatiguing than much lower risers with large treads, within certain limits. The findings indicate that there is a relationship between the human pace and the riser-tread ratio, but the relationship is more flexible than Blondel envisaged. The formulas of Blondel and his successors were too restrictive, too narrowly idealistic, and insufficiently responsive to human adaptability. The range of riser-tread options at any level of energy expenditure cannot be expressed satisfactorily by a linear equation, for the alternatives form a surface rather than a line.

2.4 Gait, Missteps, and Stair Geometry

Another approach to stair geometry is to examine its effect on gait. Whether missteps and arrhythmias are related to stair geometry has been studied through gait analysis of the locomotor processes exercised during stair use. This study (Templer 1974, 140) concluded that stair gait is influenced by stair riser-tread geometry and speed of climb.

2.4.1 Ascent

The influence of gait is less noticeable in ascent, where much less of the shoe needs to be placed on the step. Nevertheless, risers from 6.3 to 8.9 inches (16–22.6 cm) cause fewer missteps. Small risers create flights with more risers and therefore more opportunities to trip.

2.4.2 Descent

The steeper the stair is, the more missteps there are in descent, and at steep angles, where the treads are small, the performance is poorest. The larger goings—11.5 to 14.2 inches (29.2–36 cm)—generate the fewest missteps, and generally stairs with goings less than about 9 inches (22.9 cm) perform very poorly. Stairs with risers from 4.6 to 7.2 inches (11.7–18.3 cm) and goings greater than 9 inches (22.9 cm) seem to have the safest potential in descent, particularly if the angle is low and the pedestrian is descending slowly.

2.4.3 Design Implications

Because descent has been shown to be the movement direction that is most hazardous, the requirements for safe movement in descent should be of first importance. On the basis of these findings, a reasonable compromise would be a stair with risers that are not less than 6.3 inches (16 cm) to suit ascent, and risers not more than 7.2 inches (18.3 cm) and goings greater than 9 inches (22.9 cm) to suit descent.

2.5 Foot and Going Dimensions

The evidence that small goings induce missteps suggests that one should consider them in relation to human dimensions. Tread dimensions, for example, are not always large enough to accommodate the length of the shod foot, thereby forcing stair users into curiously contorted gaits. Ward and Beadling (1970, 515) recorded the positions where a group of test subjects

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placed their feet while ascending and descending three different laboratory stairs; the stairs had treads of 9.17, 10.4, and 11.0 inches (23.3, 26.4, and 27.9 cm). They noted that the subjects consistently placed a greater proportion of the shoe on the tread during descent than during ascent. (In the gait analysis tests at Haverstraw, it was noted that in ascent some people climbed without ever putting their heels onto the step; in descent, when this was possible, people often tried to locate the toes of their shoes close to or overlapping the nosing.) Ward and Beadling also found that feet were not always placed at right angles to the line of the edge of the nosing. Furthermore, the angle that the foot made with the riser was consistently less in descent than in ascent. When the treads were narrow, the subjects tended to twist their feet sideways in descent relative to the line of travel in order to gain greater area of support for their feet and to ensure a more secure base. The more the tread of the steps was narrowed, the more the feet were twisted sideways. This demonstrated a natural effort to provide the leading foot with an adequate area to resist forward momentum and slippage in descent. It also suggests that, in descent, treads that are perceived as being narrower than the shoe length engender a gait that is increasingly distorted as the treads are narrowed.

Recommended minimum tread dimensions that were adequate for people of Blondel's time in the seventeenth century or even at the beginning of this century may no longer be adequate, for average foot length, like stature, has generally increased. Damon et al. (1971, 115) show that, today, women's foot length, without shoes, varies from 8.3 to 10.7 inches (21.1–27.2 cm), and men's foot length varies from 9.2 to 12.0 inches (23.4–30.5 cm). For men's street shoes, an additional 1.2 inches (3 cm) is necessary.

TABLE 2.1
Foot and Shoe Sizes, in inches (cm)

	Population	
	99th Percentile	*95th Percentile*
Foot length	*11.8 (30)*	*11.4 (29)*
Addition for shoe	*1.2 (3)*	*1.2 (3)*
Total	*13.0 (33)*	*12.6 (32)*

A minimum size for goings can be calculated (table 2.1). A space to accommodate the shod foot adequately will need to be 12.6 to 13.0 inches (32–33 cm). We must also allow a minimal tolerance between heel and riser in descent of ¼ inch (6 mm) and assume that 1¾ inches (4.4 cm) of shoe projection beyond the nosing is about the limit for stability (to ensure that the metatarsal heads will be on the tread):

12.6 inches (32 cm) for foot and shoe
+ 0.25 inches (0.6 cm) tolerance, heel to nosing
− 1.75 inches (4.4 cm) overlap of shoe to nosing
11.1 inches (28.2 cm) total length of tread

This suggests that a going of about 11 to 11½ inches (27.9–29.2 cm) is a reasonable minimum to accommodate 95 percent of the population. This figure is considerably greater than the legal minimum of 9½ to 10 inches (24.1–25.4 cm) permitted in some codes. Goings that are less than 11 inches (27.9 cm) will enforce a distorted gait on those with large feet. It might therefore be anticipated that narrower treads would

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generate greater numbers of arrhythmic incidents during descent. Arrhythmic movement also requires greater energy expenditure.

2.6 Etiological Studies

Before attempting to draw conclusions from the studies of energy expenditure, gait, preference, and human dimensions, it is necessary to see if there is any supporting evidence from stair accident surveys. Are there studies that confirm a causal relationship between riser and going geometry and stair accidents?

Two of the earliest studies (Miller and Esmay 1961, 3; Velz and Hemphill 1953) concluded that the accident rate was not significantly higher for any particular stair angle. This does not, of course, exclude the possibility that at any given angle certain riser-going combinations are more dangerous than others. Soon after these two studies, another researcher (Jones 1963, 68) examined riser heights and tread depths as variables apart from slope. He found no significant difference in the average riser height and the average tread depth between the accident group and a sample group of stairs. However, average riser height and tread depth is not a useful measure. A more detailed analysis of the statistics might have shown that the averages concealed considerable differences.

Based on a 1969 survey by the Department of Housing and Urban Development, a 1972 report (Teledyne Brown Engineering, 2–13) concluded that nearly a quarter of all stair accidents were caused by "steep stairways and/or narrow treads." However, in a carefully constructed study published in 1978, the authors of another study (Carson et al. 1978) found that "accident rates are not related significantly to . . . dimensions." An examination of these data reveals that only 3 of the 173 stairs in the survey had goings smaller than (the critical) 9 inches (22.9 cm). Similarly, 92 percent of the stairs had risers of between 6.5 and 8 inches (16.5–20.3 cm), a moderately safe range according to the gait analysis; stairs with risers of 7 and 8 inches (17.8 and 20.3 cm) had the same accident rates, and the stairs with 7.5-inch (19.1 cm) risers had the lowest accident rates.

The study by the Bureau of Standards (Templer et al. 1978) reported that risers less than 6.25 inches (15.9 cm) and goings less than 12 inches (30.5 cm) could be classified as high risk compared to stairs with larger risers and smaller goings. Finally, from a study of stairways in workplaces (for the National Institute of Occupational Safety and Health, NIOSH) the authors (Templer et al. 1985) reported that "higher than average incidence rates were found when effective riser heights exceeded 7⅛ inches (18 cm) and when the effective tread depths were less than 10⅜₁₆ inches (26 cm). Using the standard deviations to identify dimensions more closely associated with lower incidence rates, it was found that the safest stairs would have a maximum effective riser height of 6 inches (15 cm) and a minimum effective tread depth of 11 inches (27 cm)."

What can one conclude from the somewhat contradictory and disparate nature of these studies? The 1960s studies seemed to deny that step dimensions affect accident rates, but their data were dealt with in ways that raise questions about their conclusions. The report based on the 1972 HUD data indicted "steep stairways and/or narrow treads" and recommended risers

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that are not more than 7½ inches (19.1 cm) and treads not less than 10 inches (25.4 cm). For exterior stairs attached to a dwelling, they recommended a maximum riser height of 6 inches (15.2 cm) and a minimum going of 11 inches (27.9 cm). For unattached exterior stairs, they suggested a maximum riser height of 5 inches (12.7 cm) and a going of 14 inches (35.6 cm) minimum.

One of the two NBS studies had an inadequate range of step dimensions to be of much assistance to us; the other found that small risers and goings are more hazardous. Finally, the 1985 NIOSH study seems to provide the strongest evidence that step dimensions affect incident rates.

The preponderance of the evidence from the etiological studies inclines one to conclude that goings less than 9 inches (22.9 cm) are hazardous and that 7½ inches (19.1 cm) is a reasonable maximum for safe risers. However, it is obvious that further studies are needed.

2.7 Conclusions

After considering the studies of preference, energy expenditure, foot dimensions, and etiology, we can set out recommendations for safety and comfort:

Recommendations for safety:

- In terms of gait, risers should be 6.3 to 7.2 inches (16–18.3 cm) and goings should not be less than 9 inches (22.9 cm).
- The etiological studies suggest that risers should not exceed 7.5 inches (19.1 cm) and goings should not be less than 9 inches (22.9 cm).
- To accommodate feet adequately, goings should not be less than 11 inches (27.9 cm).

Recommendations for comfort:

- From the preference studies, we learn that people prefer lower risers.
- In terms of energy expenditure, higher risers are more fatiguing. However, higher risers with smaller treads are no more fatiguing than much lower risers with larger treads.

Within these constraints, there is a useful range of riser-tread ratios with risers from 4.6 to 7.2 inches (11.7–18.29 cm) coupled with goings from 11 to 14 inches (27.9–35.6 cm) or more; at these levels, the rate of energy expenditure remains fairly low, and the number of missteps will be predictably small. From all the investigations, then, the range of dimensions shown in table 2.2 fulfills the criteria of comfort and safety best (within the range of the laboratory observations).

2.8 Risers and Goings for Helical Stairs

For helical stairs, obviously the going varies in proportion to the distance from the center of the radius. It is important that at the predicted walking line (the imaginary line along which the feet travel while using the helical stair), the going should be adequate. People do not walk with their bodies touching the handrail or adjoining wall; they leave a space. It is not clear from any studies how large this space is for people using helical stairs, but in common European usage, 10.6 inches (27.0 cm) is judged to be the distance between the walking line and the inside of a handrail or the newel.

To adhere to the same standards recommended for straight flight stairs—11-inch (27.9 cm) minimum going at the walking line—the helical stair will need a minimum diameter of about 6 feet, 9 inches (2.06 m) (Webber 1983, 14–18).

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TABLE 2.2

Range of Rise and Going Relationships for Comfort and Safety

Rise	*Goings*						
INCHES							
7.2	*11*						
7	*11*						
6.5	*11*	*11.5*	*12*	*12.5*			
6	*11*	*11.5*	*12*	*12.5*	*13*	*13.5*	*14*
5.5	*11*	*11.5*	*12*	*12.5*	*13*		
5	*11*	*11.5*	*12*				
4.6	*11*						
CENTIMETERS							
18.3	*27.9*						
17.8	*27.9*						
16.5	*27.9*	*29.2*	*30.5*	*31.8*			
15.2	*27.9*	*29.2*	*30.5*	*31.8*	*33.0*	*34.3*	*35.6*
14.0	*27.9*	*29.2*	*30.5*	*31.8*	*33.0*		
12.7	*27.9*	*29.2*	*30.5*				
11.7	*27.9*						

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TABLE 2.3

Dimensions for Spiral Stairs: Going Depth at Walking Line[a]

INCHES

Exterior Diameter of Stair	54	60	66	72	78	84	90	96	102
Diameter at Walking Line	32.7	38.7	44.7	50.7	56.7	62.7	68.7	74.7	80.7

Number of treads in circle	*Going depth at walking line*[b]								
11	9.22	10.90	12.60						
12		10.01	11.57	13.13					
13		9.26	10.70	12.14	13.58				
14			9.96	11.29	12.63	13.96			
15			9.30	10.55	11.80	13.04			
16				9.90	11.07	12.24	13.41		
17				9.32	10.43	11.53	12.63	13.73	
18					9.85	10.89	11.94	12.98	
19					9.34	10.33	11.31	12.30	13.29
20						9.81	10.75	11.69	12.63

CENTIMETERS

Exterior Diameter of Stair	140	150	160	170	180	190	200	210	220	230	240	250
Diameter at Walk Line	86	96	106	116	126	136	146	156	166	176	186	196

Number of treads in circle	*Going depth at walking line*[c]											
11	24.2	27.0	29.9	32.7	35.5							
12		24.8	27.4	30.0	32.6	35.2						
13			25.4	27.8	30.2	32.5						
14			23.6	25.8	28.0	30.3	32.5	34.7				
15				24.1	26.2	28.3	30.4	32.4	34.5			
16					24.6	26.5	28.5	30.4	32.4	34.1		
17					23.2	25.0	26.8	28.7	30.5	32.3	34.2	
18						23.6	25.4	27.1	28.8	30.6	32.3	34.0
19							24.0	25.7	27.3	29.0	30.6	32.3
20							22.8	24.4	26.0	27.5	29.1	30.7

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[a]*Exterior diameter and exterior radius are measured from the inside of the outer handrail of the stair; walking line is estimated as 10.63 inches (27 cm) from the inside of the outer handrail.*

[b]*Going at walking line is calculated from* $2 \sin\alpha/2(r_{ex} - 10.63)$, *where* r_{ex} *is the exterior radius of the stair and* α *is the angle between the front and back lines of a tread. Values to the right of the stepped line are acceptable.*

[c]*Going at walking line is calculated from* $2 \sin\alpha/2(r_{ex} - 27)$, *where* r_{ex} *is the exterior radius of the stair and* α *is the angle between the front and back lines of a tread. Values to the right of the stepped line are acceptable.*

TABLE 2.4

Going Dimensions for Helical Stairs with an Open Well

Number of Treads in Circle	*22.5*	*25.7*	*30*	*36*	*45*	*60*	*90*
Tread Angle (degrees)	*16*	*14*	*12*	*10*	*8*	*6*	*4*
Distance from center of circle (feet)	*Going dimension (inches)*						
3	*10.0*						
4	*13.4*	*11.7*					
5	*16.7*	*14.6*	*12.5*	*10.5*			
6	*20.0*	*17.5*	*15.1*	*12.6*	*10.0*		
7		*20.5*	*17.6*	*14.6*	*11.7*		
8			*20.1*	*16.7*	*13.4*	*10.0*	
9				*18.8*	*15.1*	*11.3*	
10					*16.7*	*12.6*	
11						*13.8*	
12						*15.1*	*10.1*
13						*16.3*	*10.9*
14						*17.6*	*11.7*
15							*12.6*
Distance from center of circle (meters)	*Going dimension (centimeters)*						
0.91	*25.3*						
1.22	*33.9*	*29.7*	*25.5*				
1.52	*42.3*	*37.0*	*31.8*	*26.5*			
1.83	*50.9*	*44.6*	*38.3*	*31.9*	*25.5*		
2.13			*44.5*	*37.1*	*29.7*		
2.44				*42.5*	*34.0*	*25.5*	
2.74					*38.2*	*28.7*	
3.05						*31.9*	*21.3*
3.35						*35.1*	*23.4*
3.66						*38.3*	*25.5*
3.96							*27.6*

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3 SLOPE, SURFACE, AND SLIP RESISTANCE

Ramps have just as long a history as stairs, but they have never been as prevalent as a building element. The reason is not difficult to find: for an equal rise and width, they occupy about five times as much floor space as stairs.

Aside from space considerations, ramps offer clear advantages over stairs. They are less physically demanding on users. Any ramp with a gradient that is not too steep for pedestrians, traversed at normal speeds, demands a lower *rate* of energy expenditure than any stair in general use does. When we climb a ramp at a normal pace, our heart does not beat as fast nor do we breathe as hard as on stairs. Furthermore, where knee angle and ankle angle movement is restricted for any reason, a ramp may be easier to use than a stair (Corlett et al. 1972). For the elderly and those with cardiovascular problems, arthritis, or diminished strength, ramps may be a better choice than stairs.

Ramps are also inherently less dangerous than stairs. A fall on a ramp is less likely to cause severe injuries than a fall on a stair. On even a steep ramp, the center of gravity of the victim can drop only a short distance before the body strikes the floor surface; the center of gravity of a stair user may drop as much as 6 feet (1.83 m) before some part of the body strikes the stair, and even then, the victim may continue to

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tumble down the remainder of the flight. The force of the impact in a fall, and usually the severity of the injury, is proportional to the height of the fall (if all the other factors are the same). Furthermore, on a stair during an accident, the victim is likely to strike the nosing edge of the steps. This concentrates the force of the impact into a relatively small area and is likely to be more destructive. A fall on a ramp, on the other hand, is probably not much worse than a fall on the level.

Ramps are also more effective than stairs for easing the movement of crowds of people. They slow the flow of mass pedestrian movement less than stairs do, so they are particularly suitable, and safer than stairs, for access and egress ways for theaters, stadia, and other places where there are crowds moving and people may be easily distracted from the act of seeing and using steps.

Finally, ramps offer much less of a barrier to wheeled vehicles such as wheelchairs, stretchers, and shopping carts than steps and stairs do.

Ramps, however, are not for everyone. Many people who use crutches, and others who have certain kinds of balance problem, will avoid ramps and use stairs if given the choice. Within buildings, therefore, stairs or elevators are necessary alternatives to ramps.

3.1 Ramp Safety

The design of a safe ramp is less complex than design of safe stairs. The main concerns are for a safe layout and gradient, a slip-resistant floor surface, and handrails and guardrails. A safe layout for ramps follows the same principles necessary for a safe stair layout:

- People using a ramp should not have to exit into congested or hazardous areas.
- Curb ramps should aim wheelchair users not toward the center of a street intersection, where the traffic is, but into the crosswalk.
- Landings and spaces where people may be crushed during emergency evacuations are potentially dangerous.
- A minimum of 66 inches (1.68 m) is needed at the top and bottom of ramps as a space for wheelchairs to slow down, stop, and change direction. For crowd movement, the space at the top and bottom of the ramp must not restrict the flow.

3.2 Ramp Gradients

The ancients used to make the sloping one [ramp] as easy and as little steep as possible, and as I have observed from their Works, thought it a convenient Ascent when the highest Part of its Perpendicular was raised one sixth Part of the Line at Bottom.
(Alberti 1986, 19)

A ramp may be dangerous because it is too slippery, too steep to use without losing one's balance (even if one does not slip), or even not steep enough. It may be dangerous because it is too long for some people to use without becoming unduly exhausted. The ramp's gradient affects each of these conditions.

3.2.1 A Minimum Gradient

The rule that there is no lower limit to ramp gradient has at least one exception: visually impaired people who use a long cane for guidance may not be able to detect the place where a level sidewalk (for instance) changes into a curb ramp if the slope of the curb ramp is less than about 1:16. Therefore, some less skilled visually

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impaired travelers may inadvertently stray into the street. These gentle ramps must be made detectable to cane users to provide a clue that a street lies ahead (Templer 1980).

3.2.2 A Maximum Gradient

Professional design reference books such as *Time Saver Standards* (Callender 1982) chart ramp gradients from 0 percent to 30 percent (1:3.33). Various U.S. building and fire codes specify permissible maximum gradients ranging from 9.5 degrees (1:6) to 4.75 degrees (1:12); 5.7 degrees (1:10) is the most common figure. The codes exhibit no consensus on a safe maximum gradient because it is difficult to set a figure—rather like trying to decide on a safe speed limit for cars in town. As a generalization, the steeper a ramp is, the more dangerous it becomes—if all other factors remain the same. All factors do not remain the same, however. Some flooring materials are more slippery than others, some ramps are more likely to receive precipitation and other lubricants than others, and some ramps must be designed for access for special populations.

One way to try to reach a reasonable conclusion is to examine human physiological limits. The steepness of any slope on which one can walk using a normal walking gait is limited by the ankle joint's restricted ability to rotate. In ascent, the ankle's range of motion is limited to a maximum angle of flexion of about 20 degrees, so we cannot ascend any ramp steeper than 1:2.7 with a normal gait (table 3.1). Similarly, we cannot descend a ramp that is steeper than 50 degrees (1:0.8) while using normal walking gait. If we encounter a slope that is across our direction of movement such as the flare of a curb ramp, our foot cannot invert to an angle of more than 35 degrees (1:1.4) or evert to more than 20 degrees (1:2.7). If we are wearing boots or high heel shoes, or if we have a prosthetic leg or the ankle is in a cast, even these ramp slopes would be beyond the range of a normal gait. These conclusions are of limited use, however, because no U.S. building code permits slopes as steep as these.

Tests of elderly and disabled people using short ramps (Templer et al. 1980) show that ramps steeper than 1:8 are inaccessible or difficult to use in ascent or descent. If they are very difficult to use, more accidents may result. Table 3.2 shows acceptable ramp gradients. Ramps as steep as 1:8 are acceptable for ascending or descending

Table 3.1
Ramp Gradients and the Range of Motion of the Ankle

Ankle Position	*Range of Motion (degrees)*	*Ramp Gradient*
Dorsiflexion (toes up)	*0–20*	*1:2.7 (ascent)*
Plantarflexion (toes down)	*0–50*	*1:0.8 (descent)*
Inversion (foot tilted inward)	*0–35*	*1:1.14*
Eversion (foot tilted outward)	*0–20*	*1:2.7*

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TABLE 3.2

Acceptable Ramp Gradients, Maximum Rise and Length

Gradient	*Maximum Rise in Single Run*	*Total Length, Excluding Landings*
1:8–1:10	*3 inches (7.6 cm)*	*24–30 inches (61–76 cm)*
1:10.1–1:11	*9 feet (2.74 m)*	*91–99 inches (28–30 m)*
1:11.1–1:13	*14 feet (4.27 m)*	*155–182 inches (47–55 m)*
1:13.1–1:15	*16 feet (4.88 m)*	*210–240 inches (64–73 m)*
1:15.1–1:16	*20 feet (6.10 m)*	*302–320 inches (92–98 m)*

Note: building, fire, and handicapped codes may require different gradients.

Source: Templer et al. (1980).

heights of no more than 3 inches (7.6 cm). For a height greater than 3 inches, a maximum slope of 1:10 is recommended. For heights greater than 6 inches (15.24 cm), a maximum gradient of 1:12 is recommended.

For people with disabilities, the problem of maximum gradient is linked to physical strength and stamina. A ramp that is too long, with no landing or resting place, may be daunting or even unsafe. Manual wheelchair users may lose control. For ramps that can be ascended by at least 80 percent of those who use manual wheelchairs, table 3.2 shows recommendations made on the basis of research (Templer et al. 1980). These findings differ from the 1:12 maximum gradient permitted in most U.S. codes and standards directed at access for the disabled. These codes do not take into account the bodily strength and effort that long ramps demand. Research findings indicate that if an ascent is less than 9 feet (2.74 m), 1:10 may not be too demanding. On the other hand, for a climb of 16 feet (4.88 m), 1:12 is too steep for some wheelchair users.

Even with a gradient that is not too physically demanding, landings are necessary as resting places. Therefore, most codes and standards limit the distance between landings to 30 feet (9.14 m). This standard, however, does not take into account that fatigue is related to the distance climbed (assuming a constant speed of ascent) as well as to the steepness of the slope. Because users require more frequent resting places as they become more fatigued, the distance between landings should be made progressively smaller. The recommendations shown in table 3.3 reflect this approach and the research findings on which they are based.

3.3 Gait and Falls on Ramps

Walking on stairs imposes a comparatively artificial motion that demands a high degree of precision, skill, and concentration. Human gait on ramps is very different from gait on stairs; in fact ramp gait is similar to the gait we use on level ground. Much less precision of movement is required and less attention and concentration than is required for stairs.

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TABLE 3.3

Maximum Length between Landings on Ramps

	Gradient					
Maximum Ramp Length	*1:15.9*	*1:14.3*	*1:13.7*	*1:12.7*	*1:11.6*	*1:10*
IN FEET						
Between bottom and landing 1	*95 (5.9)*	*85 (6.0)*	*80 (5.8)*	*75 (5.9)*	*65 (5.6)*	*45 (4.5)*
Between landing 1 and 2	*75 (10.7)*	*70 (10.9)*	*65 (10.6)*	*55 (10.3)*	*55 (10.3)*	*45 (9.0)*
Between landing 2 and 3	*45 (13.5)*	*45 (14.0)*	*45 (13.9)*	*45 (13.8)*	*45 (14.2)*	
Between landing 3 and 4	*30 (15.4)*	*30 (16.1)*	*30 (16.1)*			
Between landing 4 and 5	*30 (17.3)*					
Between landing 5 and 6	*30 (19.2)*					
IN METERS						
Between bottom and landing 1	*29 (1.8)*	*30 (1.8)*	*24 (1.8)*	*23 (1.8)*	*20 (1.7)*	*14 (1.4)*
Between landing 1 and 2	*23 (3.3)*	*21 (3.3)*	*20 (3.2)*	*17 (3.1)*	*17 (3.1)*	*14 (2.7)*
Between landing 2 and 3	*14 (4.1)*	*14 (4.3)*	*14 (4.2)*	*14 (4.2)*	*14 (4.3)*	
Between landing 3 and 4	*9 (4.7)*	*9 (4.9)*	*9 (4.9)*			
Between landing 4 and 5	*9 (5.3)*					
Between landing 5 and 6	*9 (5.9)*					

Note: figures in parentheses show total height ascended.

Walking on a ramp includes the same toe-off, swing phase, heel strike, and stance phase typical of the gait cycle for walking on the level (figure 3.1). However, videotape observations (Turner and Collins 1981) show that people compensate for the slope by leaning forward when walking up a ramp, and backward when walking down. In other words, natural caution and gait control demands that we lean in the direction where the effects of a fall will be minimized and where the probability of recovering balance is maximized.

Most injurious accidents on ramps occur during descent, and most are caused by slips. Usually these accidents occur as the weight is being transferred onto a foot at heel strike at the end of the swing phase. If the frictional force between foot and ramp is insufficient to effectuate the weight transfer during toe-off and heel strike, then a slip may occur. In descent, the foot, and specifically the back of the heel, may have considerable residual motion as it moves forward, descends toward and contacts the ramp, and this tends to amplify the tendency to slip. Much of the weight of the body is transferred to the back of the heel at the moment of impact. If the frictional force between heel (usually) and ramp is inadequate, the foot will tend to continue forward in a slip. This explains why people who slip and fall on ramps often state that their feet "went out from under them." If the victim has been leaning back slightly (as is usual), then a fall onto the other leg (rear) in some sort of a sitting or kneeling position or a fall backward or sideways is likely to occur; if there is sufficient forward momentum in the body, the victim may even fall forward with front leg outstretched.

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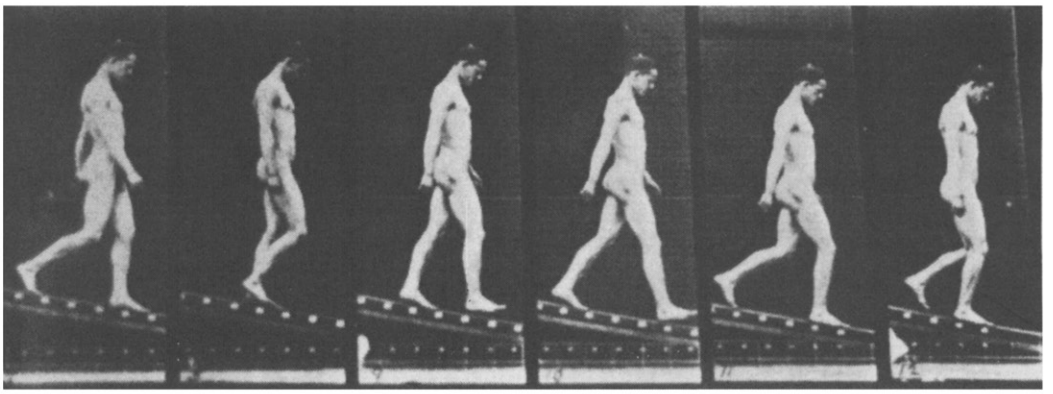

3.1 *Gait during ramp descent, reprinted from Muybridge (1955), 12*

Falls caused by slips during descent usually occur because the victim does not perceive or realize that the ramp has a hazardous combination of steepness and slipperiness. The victim may even assume that the ramp is safe because it has been provided for use and is used by others—even if it seems to be steep. The accident may also be caused because the victim is walking too fast and is taking very large steps, because the shoe soles and heels are too slick, or because something on the surface of the ramp is acting as a lubricant and reducing the coefficient of friction.

An injurious fall is less likely to occur in ascent because the forces present are smaller. If the ramp is very slick, a slip may occur during heel strike. Alternatively, the fall may be caused by a slip during toe-off. In this case, the rear foot slips backward as a reaction to the thrust against it. Again, the slip results from inadequate frictional resistance between the sole of the shoe and the ramp. There is less likelihood of a fall if much of the body's weight has been transferred to the leading foot. As the rear foot slips back, with the forward foot stationary, the body tends to fall into a kneeling position. If the victim is able to lift the rear foot after the commencement of the slip, an attempt may be made to break into a run to try to recover the lost balance. If this is unsuccessful, the victim may pitch forward onto hands and knees.

The feet are more or less stationary at the start of a swing phase in ascent or descent. If the ramp and the shoes are very slippery, however, then the victim's feet may start to slide down the ramp, responding to the pull of gravity.

3.4 Frictional Forces

The recommendations for ramp gradient and length apply to ramps where the floor surface material provides adequate frictional resistance. A ramp of any gradient may be dangerous if it is slippery.

The number of people who fall after slipping on the floor is not certain, although European studies quoted by Manning et al. (1983, 703) indicate that more than half of all falls result from slipping.

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Swedish official statistics, for example, show that 57 percent of workers who fell on the same level had slipped (Strandberg 1983, 11–32).

Society makes an attempt to control slip resistance in building and fire codes by calling for a nonslip or nonskid surface, but these terms are not expressed quantitatively, and mensuration standards or techniques are rarely defined. The vagueness of these terms restricts code effectiveness. There are some standards for floor surface slip resistance but no comparable standards for controlling the slipperiness of shoes, and the coefficient of friction is as much dependent on the shoe materials (and particularly the heels) as on those of the walkway. Some shoes have soles and heels that are as smooth as glass, and many types of shoe material remain relatively slippery permanently. Until manufacturers can be persuaded to limit the slipperiness of shoes, any recommendations for a coefficient of friction standard for floor surfaces should assume that some pedestrians will be using new and perhaps slippery shoes.

3.4.1 Acceptable Friction Forces

People slip when they encounter a surface where the coefficient of friction (COF) between shoe and floor is inadequate for the forces present. To determine a COF value that will prevent slips, two factors must be considered: the magnitude of the horizontal and vertical forces transmitted to the floor by the feet during ambulation and the capability of the flooring and shoe materials to resist these forces. The search for an acceptable level of frictional resistance is far from new; even Leonardo da Vinci was interested in the subject. The laws of friction enunciated more than two hundred years ago by Amontons (1699) and Coulomb (1781) state that:

1. The frictional force (F) that opposes the tendency to slip is proportional to the normal (vertical) force (N). The constant term of the proportion is termed the coefficient of friction (COF), μ. Then $F = \mu N$ and therefore $\mu = F/N$.

2. The COF is independent of the area of contact.

3. The COF is independent of the velocity between the two surfaces. This law, according to Brungraber (1976) is frequently violated at very high or very low rates of motion.

The subject of acceptable slip resistance levels has little consensus. As Strandberg says, "No method or apparatus has achieved international acceptance for universal slip-resistance measurements. A universal procedure seems to be a utopia, if all demands (from field to laboratory tests, from general walking surface evaluation to shoe component optimization, from dry to lubricated conditions, from spot to area measurements, from average to variation measures and so on) must be met by one apparatus, where the cost/benefit ratio is reasonable from the user's point of view" (Strandberg 1983, 11–32).

COF is dependent on more than the characteristics of the floor surface. The minimum value of COF needed for safe locomotion is also affected by waste deposits and precipitation on the surface, temperature and humidity, the composition of the materials of the shoes, any coating on the floor material, the fit of the shoes, individual gait and speed, age, physical condition, and walking skill, direction of movement,

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type of task being performed (perhaps pushing something), and behavioral responses (Pfauth and Miller 1976, 77–90). Not all of these can be accurately assessed, and certainly not their cumulative and interactive affects.

The first part of the international controversy revolves around whether static or dynamic COFs are the most meaningful, and there is equipment available for measuring either or both. (Assuming a constant normal force, say the weight of a block resting on a surface such as the floor, the static coefficient relates to the tangential force needed to start the block in sliding motion while its dynamic coefficient relates to the tangential force needed to continue motion once it has started.) As Perkins points out, "Some workers consider the static COF to be important as no movement between shoe and ground is detected during walking, whereas others suggest that rotation between shoe and ground does occur or that the shoe does not stop moving and the dynamic COF is more important" (Perkins 1978, 71–87). Nevertheless, he concluded that the static coefficient is the most relevant for slip-resistance testing.

In the United States, a preference for static values has been shown recently. The Underwriters Laboratory and the ASTM Test for Static COF of Polish-Coated Floor Surfaces as Measured by the James Machine (D 2047-82) require static tests (and a minimum COF of 0.5), and the latter was, until recently, the only method issued as an ASTM standard.

Can slip resistance be controlled by specifying minimum values of COF? It is not unusual to find that a static COF of 0.5 is recommended as a minimum COF. Is this the correct value? Miller (1983, 145–158) set up a tabular summary of key quantitative findings by various writers going back to 1943 and noted that "the minimum required COF for normal pace walking . . . ranges between 0.2 and 0.4 depending on the author's research methodology" and depending, one might add, on whether the author has included a safety factor.

Three methods have been used as the basis for these recommendations for COF: the friction coefficient of walkway surfaces known to have a good safety record, experimental kinesiology—measurements of the forces exerted by the shod foot on the floor (Perkins 1978)—and anthropometry, in this case, the geometry of the body while walking is made the subject, or object, of the resolution of forces. The argument in this case is as follows (fig. 3.2): if one can establish the force exerted by the forward heel as it contacts the floor surface, then the magnitude of the force needed to react to it to prevent it from sliding forward will be established. The force (R) conveyed to the heel through the forward leg can be resolved into its horizontal (F) and vertical (N) components.

If θ is the angle that the forward leg makes with the vertical, then $\sin \theta = F/R$ and $F = R \sin \theta$ and $N = R \cos \theta$. To find μ, the COF needed to limit forward (sliding) movement, $\mu = F/N$ (by definition) so,

$$\mu = \frac{R \sin \theta}{R \cos \theta} = \tan \theta.$$

Therefore, given the length of the leg from hip to heel (L) and the length of half of the pace, then the angle can be established and hence the COF. For example, if L for a 50th-percentile man is 36.4 inches and the

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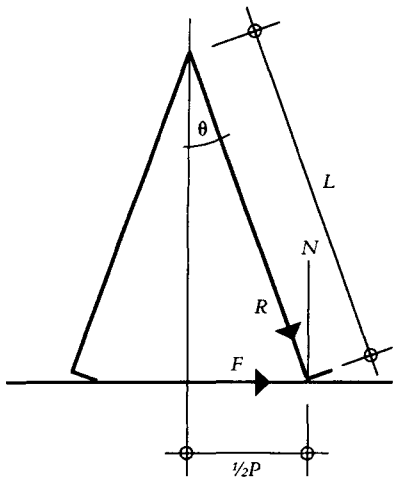

3.2 Slip forces present in horizontal walking

length of his pace at an average walking speed is 28.2 inches with a half pace of 14.1 inches, then

$$\sin \theta = \frac{14.1}{36.4} = 0.387$$

$$\theta = 22.79°$$

so the limiting COF

$$\mu = \tan \theta = 0.42.$$

It would be difficult for anyone to take a stride long enough to make the tangent of the apex angle exceed the 0.5 coefficient of a slip-resistant floor; people may not slip even if the COF is 0.3 to 0.45; 0.5 simply adds a safety factor (Pfauth and Miller 1976, 77–90). However, as Brungraber (1976) points out, a person running, and therefore using a much longer stride, may well need a COF of 1.1. Clearly none of the recommendations is intended to provide slip resistance for a person running. Similarly, the COF recommendations do not pay attention to the increased frictional requirements or motions as one makes a turn while walking (Harper, Warlow, and Clarke 1967).

It follows that if one is aware that the ground is wet or icy (or is a very steep ramp) with a low frictional slip resistance, then one must (and instinctively does) shorten one's pace. So in the example, if the COF of the slippery surface is 0.2, then one would have to shorten the pace to 14.28 inches—or risk a slip.

ASTM and the Underwriters Laboratory (for polish-coated floor surfaces) and others have recommended 0.5 as a minimum value. Others have recommended values from 0.2 to 0.7, but there is no international or even national consensus. A COF of 0.5 includes, by all accounts, a safety factor and therefore has some merit as a cautious recommendation (particularly as a precaution against slippery shoes). If, however, a floor surface does not meet this standard, it does not follow that it is dangerously slippery; 0.4 or even 0.3 may be the minimum for safety. A COF of 0.5 is no guarantee that people will not slip on it; it may not provide adequate protection for people running, turning left or right, walking on ramps or on wet surfaces, or using slippery shoes. Furthermore, a recent empirical study of a small number of subjects (Kulakowski et al. 1988) suggests that 0.5 may not be adequate for the disabled and therefore many of the elderly. Table 3.4 lists the dry COF (static) or a range of materials as established in the laboratory. Table 3.5 shows wet and dry values.

3.4.2 Wet Surfaces

Lubricating the contact area between shoe and floor surface with water, oil, dust, or any similar substance may substantially reduce the COF. Nearly all combinations of

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TABLE 3.4

Coefficient of Friction for Selected Dry Materials

Material	*Leather Shoe*	*Neolite Shoe*
Brushed concrete, new, against grain	*0.75*	*0.90*
Asphalt tile, waxed, heavy use area	*.56*	*.47*
Smooth steel, rusted slightly	*.54*	*.49*
Asphalt, old, in parking lot	*.53*	*.64*
Steel checker plate, rusted moderately	*.50*	*.64*
Quarry tile, unglazed	*.49*	*.60*
Thermoplastic, old, on crosswalk	*.45*	*.86*
Brick pavers, new, on stair	*.43*	*.73*
Exposed aggregate, pea gravel	*.41*	*.57*
Granite stairs, old, exterior	*.40*	*.66*
Plywood "A" side, unfinished, with grain	*.39*	*.75*
Plywood "A" side, unfinished, against grain	*.39*	*.75*

Source: Templer, Zimring, and Wineman (1980).

TABLE 3.5

Slip Resistance of Floor and Tread Finishes

Material	*COF (dry and unpolished)*	*COF (wet)*
Clay tiles (carborundum finish)	*>0.75*	*>0.75*
Carpet	*>0.75*	*0.4 to <0.75*
Clay tiles (textured)	*>0.75*	*0.4 to <0.75*
Cork tiles	*>0.75*	*0.4 to <0.75*
PVC (with nonslip granules)	*>0.75*	*0.4 to <0.75*
PVC	*>0.75*	*0.2 to <0.4*
Rubber (sheets or tiles)	*>0.75*	*<0.2*
Mastic asphalt	*0.4 to <0.75*	*0.4 to <0.75*
Vinyl asbestos tiles	*0.4 to <0.75*	*<0.4*
Linoleum	*0.4 to <0.75*	*0.2 to <0.4*
Concrete	*0.4 to <0.75*	*0.2 to <0.4*
Granolithic	*0.4 to <0.75*	*0.2 to <0.4*
Cast iron	*0.4 to <0.75*	*0.2 to <0.4*
Clay tiles	*0.4 to <0.75*	*0.2 to <0.4*
Terrazzo	*0.4 to <0.75*	*0.2 to <0.4*

Source: Adapted from British Standards Institution (1984, 15).

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dry and clean shoes and surfaces have COF values greater than 0.5, while only selected combinations of wet shoes and surfaces result in a COF value greater than 0.4 (Miller 1983, 150).

There is a dearth of recent studies that set out the differences between COF values for wet and dry surfaces. The main reason is that most of the slip-resistance test machines give unreliable results when used on wet floors. Grandjean (1973), however, provides some values, based on Sigler's data, which date from 1943. Sigler used a pendulum-type machine, generating a dynamic measure, so Grandjean's figures should be viewed with considerable caution. He shows that the decrease in the COF of a material when it is wet may be as little as 2 percent or as much as 81 percent. The COF of granite when using leather soles decreases from 0.42 to 0.41 (2.4 percent), that of marble decreases from 0.38 to 0.22 (42 percent), that of concrete decreases from 0.38 to 0.10 (74 percent), that of ceramic tiles decreases from 0.48 to 0.45 (6 percent), and that of wooden flooring decreases from 0.40 to 0.21 (47 percent). When using rubber soles, the COF of granite decreases from 0.78 to 0.60 (23 percent), that of marble decreases from 0.80 to 0.15 (81 percent), that of concrete decreases from 0.78 to 0.20 (74 percent), that of ceramic tiles decreases from 0.82 to 0.58 (29 percent), and that of wooden flooring decreases from 0.82 to 0.40 (51 percent).

Floor surfaces exposed to the weather or any other potential lubricating factor should be finished with materials that, when wet, will still have an adequate COF, and when floors are being washed, people should not walk on them unless the wet COF is adequate. In industrial or commercial environments, where admission of people is controlled, a possible alternative would be to supply or specify the shoes to be worn.

3.5 Slip Resistance on Ramps

A flooring material that provides an adequate frictional resistance when used for level walkways may be inadequate on a ramp. Floor surfaces on a slope require a higher COF to nullify the effects of the slope. Harper et al. (1967) examined the forces involved in walking on a slope and found that they varied with a linear relationship of the form $F = a + b \tan \theta$. Consider, for example, a person walking along a sidewalk and assume that his stride is such that the COF of the sidewalk is just enough to prevent him from slipping as he walks. At the end of the sidewalk is a curb ramp, and he proceeds down the ramp. He does not shorten his pace as he walks on the ramp. Then (figure 3.3):

$$\mu_{sh} = \tan \theta$$

$$F = R \sin (\alpha + \theta)$$

$$N = R \cos (\alpha + \theta)$$

where μ_{sh} is the COF required to just prevent slipping on the horizontal sidewalk.

θ is the angle that the forward leg makes with the vertical,

α is the angle of the ramp slope,

R is the force conveyed to the heel through the forward leg, which can be resolved into its components, F along the slope of the ramp and N normal to the slope of the ramp,

μ_{si} is the apparent COF required to just prevent slipping on the incline.

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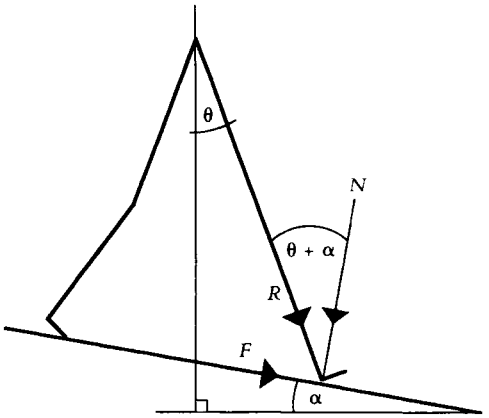

3.3 Slip forces present in ramp descent

Therefore, to prevent slipping on the ramp,

$$\mu_{si} = \frac{F}{N} = \frac{R \sin(\alpha + \theta)}{R \cos(\alpha + \theta)} = \tan(\alpha + \theta)$$

$$= \frac{\tan \alpha + \tan \theta}{1 - \tan \alpha \tan \theta}$$

$$= \frac{\tan \alpha + \mu_{sh}}{1 - \mu_{sh} \tan \alpha}$$

If the curb ramp has a gentle slope, say 1:12, then the pedestrian's speed on the ramp will probably be much the same as on the level sidewalk. If, for example, a coefficient of friction of 0.5 is required to prevent him from slipping on the level sidewalk, then the material of the curb ramp will need a coefficient of 0.61 if it is to be as effective as the level walkway in preventing slips. There is clearly an argument for choosing a ramp material that compensates for the slope.

The left-hand column in table 3.6 shows a range of coefficients of friction such as might be chosen for some level walkway. The remaining columns show the coefficients necessary to provide equal slip resistance for various ramp gradients (for pedestrians who do not change their pace on the ramp).

Now reexamining the COF of various walkway materials such as those listed in tables 3.4 and 3.5, it becomes quite clear that it is not easy to find materials that will give an adequate slip resistance for the steeper gradients. None of the materials tested had coefficients of friction greater than 0.75 (for well-used, dry leather soles), and seven of the twelve had values that were less than 0.50. Only one, brushed concrete, would have been usable on a 1:10 ramp if it was to match the performance of a level walkway with a coefficient of 0.50. This is part of the reason that steep ramps have a poor safety record, particularly ramps in the open that are not protected from precipitation and other lubricating materials.

3.6 Slip Resistance on Steps

The surface of stair treads, and of course landings, must have an adequate and uniform resistance to slip forces. Mishaps can occur at any stage in the gait cycle, although accidents caused by slips usually occur as the weight is being transferred from or onto a foot at the beginning or end of the swing phase. Because heel strike (on a walkway) presents such a small contact area, the potential for slippage is much greater than at toe-off, where much of the sole of the shoe remains in contact with the horizontal surface. If the frictional force between foot and step is insufficient to effectuate the weight transfers at first contact, and later at toe-off, the foot will slip and the body will be thrown off-balance.

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TABLE 3.6

Static Coefficient of Friction for Level Surfaces and for Various Gradients

Level	*1:20*	*1:18*	*1:16*	*1:14*	*1:12*	*1:10*	*1:8*	*1:6*	*1:4*
.80	*.89*	*.90*	*.91*	*.92*	*.95*	*.98*	*1.03*	*1.12*	*1.31*
.75	*.83*	*.84*	*.85*	*.87*	*.89*	*.92*	*.97*	*1.05*	*1.23*
.70	*.78*	*.79*	*.80*	*.81*	*.83*	*.86*	*.90*	*.98*	*1.15*
.65	*.72*	*.73*	*.74*	*.76*	*.78*	*.80*	*.84*	*.92*	*1.07*
.60	*.67*	*.68*	*.69*	*.70*	*.72*	*.74*	*.78*	*.85*	*1.00*
.55	*.62*	*.62*	*.63*	*.65*	*.66*	*.69*	*.72*	*.79*	*.93*
.50	*.56*	*.57*	*.58*	*.59*	*.61*	*.63*	*.67*	*.73*	*.86*
.45	*.51*	*.52*	*.53*	*.54*	*.55*	*.58*	*.61*	*.67*	*.79*
.40	*.46*	*.47*	*.47*	*.49*	*.50*	*.52*	*.53*	*.61*	*.72*
.35	*.41*	*.41*	*.42*	*.43*	*.45*	*.47*	*.50*	*.55*	*.66*
.30	*.36*	*.36*	*.37*	*.38*	*.39*	*.41*	*.44*	*.49*	*.59*

3.6.1 SLIPS IN DESCENT

A slip in descent may occur during toe-off or during first contact. A slip during toe-off is less likely to be serious unless the forward momentum is substantial. In this case, the pedestrian must recover at a run or fall. More likely, as the center of gravity is being held back (cautiously), the mishap will cause the person to collapse into a squat or, at worst, to fall backward or sideways.

The major risk of slipping in descent occurs if the foot is put down right onto the front edge of the tread and there is not enough frictional resistance to prevent it from sliding off, a condition that will be exacerbated by the presence of oil, water, ice, or any other lubricant. If the slip occurs during first contact, as the leading foot is lowered onto the tread, the situation is potentially serious because the body's weight may be thrown forward and outward. At this point, only agility (or perhaps a handrail) may help to restore equilibrium. Sometimes this type of slip will be caused by the leading foot's slipping off the edge onto the next step below.

Normal gait on stairs is unlikely to result in slips, however, because the peak horizontal force generated between the foot and the tread is much less than the equivalent forces generated during walking on the level. The exception is where the steps are in motion—on ships, for example.

3.6.2 PEAK FORCES DURING LEVEL WALKING

There are six distinct force peaks in level walking: four during the landing phase and two during takeoff (Perkins 1978, 71–87). The first peak is caused by the force of the impact of the heel tip against the floor—and the force has a forward direction. The second peak is a backward force caused by the heel of the shoe shortly after contact (and Perkins was unable to explain why this occurred). Peaks 3 and 4 are both forward and are caused by the main forward force, which retards the motion of leg and body. These forces occur within 0.1 seconds after heel strike with only the back of

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the heel in contact with the ground, but already a significant proportion of the body weight has been applied through the edge of the heel. This explains why so many slips occur during this period.

As the foot rocks forward, more of the shoe, particularly the sole, touches the ground and more of the body weight is transferred to this foot. The center of gravity moves over this foot, and the forward force of peak 4 decreases. As the phase continues, another peak develops—a backward force exerted by the foot propelling the body forward. The stance phase ends sometimes with a sixth peak, depending on the flexibility of the shoe as it bends during toe-off.

3.6.3 Peak Forces during Stair Descent

Force plate studies have shown that the horizontal component of foot force, in stair descent, is not great. It reaches two apogees: at first contact and at toe-off. At these moments, the force is only about 6 percent of body weight, compared to apogees of 15 and 20 percent for walking on the level, where the horizontal speeds are greater (Klopsteg and Wilson 1954, 453). *F maximum,* the frictional force, must therefore exceed this value if slippage is to be avoided. *F maximum* will depend on the magnitude of the vertical component and the coefficient of friction of the two materials (the shoe and the tread) brought into contact. From this one may conclude that an appropriate COF for stair treads might be less than for level walkways. However, considering the comparable risks of a fall from a slip and the rather small contact area between shoe and nosing edge during descent, it is unwise to use a lower COF standard.

Special attention must be paid to slip resistance at the step nosings, particularly at the landing at the top of a flight. In the area adjoining the first riser, the forward foot is likely to make contact with the floor in much the same way and with much the same horizontal speed and force as would be the case with level walking. A slip at this point may cause the victim to fall down the stairs with unusual forward velocity.

The mechanics of these slip mishaps point up the need for a large enough tread, adequately abrasive surface, particularly at the front of the tread and, out of doors, a wash or slope to throw water off the tread during rain (and to prevent ice formation).

3.6.4 Slips in Ascent

In ascent, most mishaps occur during the swing phase. The rear foot may slip during the toe-off, throwing the body forward toward the stairs. More frequently, the leading foot may trip on the riser or slip off it. A slip during toe-off is not likely to be frequent because, unlike in walking, in stair climbing the rear leg does not perform much of the work of elevating the body. This is done by straightening the forward leg. In either case—slip or trip—if the momentum cannot be checked in time by a quick repositioning of the feet, then a fall may ensue, with the nosings as potentially hazardous edges if there is an impact. For this reason, sharp edges on nosings are dangerous. Erosion of sharp edges is likely to be much greater also, and this adds a further dimension to the stair's dysfunctional propensities.

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3.6.5 Hazardous Slip-Resistance Provisions

The risks of slipping on stairs have been so overplayed in safety literature that there have been several misguided and potentially hazardous responses from the building industry. One response has been to make treads with aggressively abrasive surfaces like cheese graters (fig. 1.6), which are likely to cause accidents when the stair user trips on this very rough surface. If anyone is unfortunate enough to fall onto such a surface, the resulting abrasions are likely to be extensive.

A second response has been the development of the abrasive nosing industry. If the tread material has a poor coefficient of friction (which means that it is unsafe), then the addition of an abrasive strip to the nosing may be useful in preventing slips at that point only. Its utility will be vitiated if it causes trips because it projects above the tread surface or acts to confuse one visually as to where the edge is. For new stairs, this treatment is no substitute for an adequately abrasive surface for the whole tread, including the nosing. Some manufacturers do not recognize that it is the COF of the nosing that matters most, so many proprietary abrasive tread and nosing systems (and manufactured stair systems) provide tread surfaces with a high COF and leave the nosing edge with a potentially hazardous, slick surface.

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4 Stairway and Ramp Size for Crowds

A person may be more comfortable, may use less effort, and in fact may be safer on one flight of stairs than another of different shape. Stair geometry and human gait can be made congruent. But congruence with the physiological needs of the individual user is not enough. The presence and actions of other people on the stair may restrict the free choice of speed (and even direction) and, therefore, walking rhythm. To some extent, this is acceptable and inevitable. However, a level of interference is reached when the normal rhythmic gait patterns are forced into irregularity, or even halted, in order to avoid incipient conflicts. So once again arrhythmia results, supplemented this time by the behavioral responses of people as they try to maintain their balance.

A stair inadequate for its volume of traffic is at best irritating, is certainly uncomfortable, and may be dangerous. It is hardly responsible for a transportation spokesperson to say, as one recently did, that if the stair is congested, pedestrians will have to learn to be patient. Pedestrians in the most active sections of many great cities are habitually and inevitably patient; they have no choice. They tolerate traffic conditions on sidewalks and transportation stations that are routinely uncomfortable and overcrowded. However, comfort is as much related to our perception of what is

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safe as it is to unwanted proximal contacts and delay. People understand subconsciously how much space is needed for safe ambulation at various speeds. We begin to feel uneasy as crowds throng and start to press around us. We may be offended by their proximity, their penetration of our personal space, and certainly by unsought physical contact. And as congestion increases, what was merely distasteful and uncomfortable may become quite suddenly threatening. Body contact pressures build up, and the crowd coalesces into a unified conflux, with individual responses impossible. People are swept along and even lifted off their feet.

Fear transforms congestion into a terrifyingly destructive failure. Fear is a natural response. Precipitous flight from intolerable, unavoidable danger is instinctive in humans. Catastrophe is not caused by flight but by restrictions that inhibit or prevent escape and elicit desperate and ruthless behavior. Duane Schultz (1964, 9) cites a description of the Iroquois Theatre fire of 1903 in Chicago:

The fire escape ladders could not accommodate the crowd, and many fell or jumped to death on the pavement below. Some were not killed, only because they landed on the cushion of bodies of those who had gone before.

But it was inside the house that the greatest loss of life occurred, especially on the staircase leading down from the second balcony. Here most of the dead were either trampled or smothered, though many jumped or fell over the balustrade to the floor of the foyer. In places on the stairway, particularly where a turn caused a jam, bodies were piled seven or eight feet [2.4 m] deep. . . . An occasional living person was found in the heaps, but most of these were terribly injured. The heel prints on the dead faces mutely testified to the cruel fact that human animals stricken by terror are as mad and ruthless as stampeding cattle. Many bodies had the clothes torn from them and some had the flesh trodden from their bones.

In summing up the disaster, Schultz points out that 500 people died in just 8 minutes after the first cry of "Fire!" Ironically, the theater itself did not burn. Describing the Coconut Grove fire of 1942 in Boston, *Newsweek* (1942, 43–44) reported, "Others tripped and choked the 6-foot-wide stairway up from Melody Lounge. Those behind swarmed over them and piled up in layers—layers of corpses." Seven hundred people died or were injured in this disaster. Half of those who escaped unhurt were employees who were familiar with alternative exits (Schultz 1964, 10).

In both catastrophes, congestion was a contributory cause. The primary cause was fire, followed by a stampede in which people stormed and clogged the escape routes. It has been suggested that if the people had filed out in an orderly manner, there would have been few deaths, but this would have demanded a quite unusual and even unreasonable degree of self-control over the normal acute fear reactions, for as Schultz (1964, 5) points out, "simple flight behavior . . . is the only rational way to respond to such a life-threatening disaster."

Congestion, by definition, should never be the normal state; that would be indefensible and even hazardous at rush hour, at final curtain time at the theater, or at the close of a ballgame. This chapter discusses methods of estimating stair and walkway capacity, and planning for acceptable levels of crowding.

Congestion is often sporadic or cyclical and responds to the episodic nature of bulk

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arrival situations—of mass transit, for example. This is more difficult to allow for because a degree of congestion will, under all but the most ideal conditions, be designed into the system—an adequate capacity for most of the time and some congestion some of the time. To be responsive to people, such planning decisions should be derived from the spatial and behavioral needs of the individual pedestrian—physical, sensory, psychological, and cultural needs—as well as the expected service time of the transportation system.

4.1 Human Territoriality and Space Needs on Stairs

A pedestrian occupies a block of space and during ambulation systematically occupies and relinquishes additional space. The extra space is utilized for locomotor activity, as a buffer against physical contact with other parts of the environment, and against interactive contact with other people. In aggregate, these spatial demands, together with those of other users, determine the potential traffic flow and the necessary capacity of the stair.

The space required for pedestrian movement is dependent on four factors: the body ellipse, the pacing zone, the sensory zone, and the buffer zone. The body ellipse represents the physical dimensions of the human frame standing at rest. The pacing zone is the space necessary for the body during locomotion. In addition, two intangible but demonstrably real zones must be considered. The first of these is the sensory zone, the distance a person tries to maintain between the body and other parts of the environment, so that there will always be enough time to perceive, evaluate, and react to approaching hazards. And, finally, there is the buffer zone—the bubble of space that people maintain between themselves and others for psychocultural reasons.

4.1.1 The Body Ellipse

Time Saver Standards (Callender 1982) gives 24 inches (61 cm) as the recommended minimum width for a single-file stair (without handrails) as suitable for comfortable passage of one individual and 30 inches (76 cm) as better. Anthropometric and gait analysis data suggest that the former figure may be inadequate for as much as 40 percent of the American male population and the latter may be close to being a reasonable minimum. *Time Saver Standards* probably refers to the "average man," as the anthropometric data in the book suggest. The myth of the average man would lead us to design doors that are only high enough for a 5 foot, 9 inch person.

4.1.2 Body and Stair Width

A shoulder breadth of 21 inches (53 cm) is a reasonable design minimum for public locations (Damon 1971, 104). This would be adequate for all but the largest 1 percent of the population. To allow for heavy winter clothing, an additional 1.5 inches (3.8 cm) must be added. These figures are based on measurements of people in static positions, arms held against the sides. With the arms swinging free in the normal way during walking, about 2 inches (5 cm) extra on each side is necessary. A further 1¾ inches (4.4 cm) on either side is needed to allow for lateral displacement—the side-to-side rhythmic oscillation that occurs as the weight is transferred from one leg to the other (Dec et al. 1953, 543–558). In dense crowds, when human movement has been

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reduced to a shuffle, photographic evidence suggests that the oscillation is more pronounced—in the range of 4 inches (10 cm) on either side. On stairs, this sway pattern is similar to the more restricted locomotion in crowds (Fruin 1987, 30). Handrails occupy at least 3 inches (7.6 cm) on each side; however, no further lateral tolerance is necessary because the arm swing and lateral displacement occurs mostly above the handrail.

To allow for some clearance between clothing (but not handbags) and the adjacent wall surfaces, a further 2 inches (5 cm), say, is required—1 inch (2.5 cm) on each side. Finally, some tolerance should be allowed, particularly on stairs, for tracking error; otherwise the pedestrian must advance with mathematical precision along a straight line. Assume a minimum of 1 inch (2.5 cm) on each side. An estimate of the static and dynamic body width dimensions is shown in table 4.1.

From these figures, for ascending or descending a stair in single file, about 38 inches (96.5 cm) between walls is comfortable and 29 inches (74 cm) a minimum for use in a public place. Comparable figures for residential interiors (assuming no heavy clothing) would be 37 inches (94 cm) and 27.5 inches (70 cm). However, the effective width is mediated by the presence of adjoining walls and handrails; people maintain a distance of about 6 inches (15.2 cm) between themselves and a wall and 3½ inches (8.9 cm) between themselves and the centerline of a graspable handrail (Pauls 1982).

For people to be able to walk side by side, *Time Saver Standards* (Callender 1982, 3–313) suggests that stairs should be at least 42 inches (1.07 m), excluding space for handrails. Unless the stair is to serve a very select population, this is too little; 56 inches (1.42 m) may be a more reasonable minimum (between walls). For side-by-side stair use, it is not necessary to design for two very large people, the ninety-ninth percentile. The fiftieth percentile, about 17 inches (43 cm), is a reasonable minimum (obviously, this would not allow two very large people to walk side by side or pass with comfort). The estimated total of the effective static and dynamic dimensions is as shown in table 4.2. Thus, for stairs enclosed by walls, a usable minimum design width that will permit overtaking should be calculated on a module of at least 28 inches (71 cm), and preferably 34.5 inches (88 cm). Therefore, a stair that will allow people to walk side by side (in heavy clothing) between walls should be at least 56 inches (1.42 m) wide; 69 inches (1.75 m) is more comfortable.

4.1.3 Body Depth

The dimensions needed for body depth calculations are of considerable importance for queuing conditions but are not very well known. On the basis of a small group of college and young air force personnel (nude subjects), the maximum body depth of the fiftieth percentile is 11.5 inches (29 cm) (Damon 1971, 134). The lack of older people in the study sample probably compensates for the concurrent absence of women and children. Older people tend to be larger, and women and children tend to be smaller. For queuing and static standing situations in public places, the mean is not an unreasonable design measure where the group is likely to include large and small people.

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TABLE 4.1

Factors Affecting the Width of a Single-File Stair

	Comfortable (99th percentile)	*Minimum (95th percentile)*
Shoulder breadth	*21 inches (53 cm) (Damon 1971)*	*20 inches (51 cm) (Damon 1971)*
Heavy clothing	*1.5 inches (3.8 cm) (Damon 1971)*	*1.5 inches (3.8 cm) (Damon 1971)*
Arm swing	*4 inches (10.2 cm) (estimate)*	*4 inches (10.2 cm) (estimate)*
Lateral displacement	*approx. 8 inches (20 cm) (Fruin 1987)*	*approx. 3.5 inches (8.9 cm) (Dec 1953)*
Wall clearance	*2 inches (5 cm)*	—
Tracking error	*2 inches (5 cm)*	—
Total	*38.5 inches (98 cm)*	*29.0 inches (74 cm)*

Source: Dec et al. (1953), Damon (1971), Fruin (1987)

TABLE 4.2

Factors Affecting the Width of Stair for Side-by-Side Walking, for Each Person

	Comfortable (50th percentile)	*Minimum for Movement*	*Minimum for Stop/Start*
Shoulder breadth	*17 inches (43.2 cm)*	*17 inches (43.2 cm)*	*17 inches (43.2 cm)*
Heavy clothing	*1.5 inches (3.8 cm)*	*1.5 inches (3.8 cm)*	*1.5 inches (3.8 cm)*
Arm swing	*4 inches (10.2 cm)*	*4 inches (10.2 cm)*	—
Lateral displacement	*8 inches (20.3 cm)*	*3.5 inches (8.9 cm)*	*3.5 inches (8.9 cm)*
Wall clearance	*2 inches (5.1 cm)*	*2 inches (5.1 cm)*	*2 inches (5.1 cm)*
Tracking error	*2 inches (5.1 cm)*	—	—
Total	*34.4 inches (87.4 cm)*	*28.0 inches (71 cm)*	*24.0 inches (61 cm)*

TABLE 4.3

Estimate of Space Required for Body Depth

	For Queuing in Public	*For Elevators and Tight Queues*
Maximum body depth (mean)	*11.5 inches (29.2 cm)*	*11.5 inches (29.2 cm)*
Clothing	*2.5 inches (6.4 cm)*	*2.5 inches (6.4 cm)*
Sway	*2 inches (5.1 cm)*	—
Total	*16.0 inches (40.6 cm)*	*14.0 inches (35.6 cm)*

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To allow for heavy clothing, an allowance of 2.5 inches (6.4 cm) is necessary. A further tolerance is needed (except for extremely crowded situations such as elevators) for postural sway—the normal physiological device of the body to prevent fatigue and to facilitate the blood flow through the muscles (Astrad and Rodahl 1970, 65). However, the magnitude of the sway is conjectural; 1 inch (2.5 cm) back and front may be a modest estimate. An estimate of static and dynamic body depth dimensions is shown in table 4.3.

From these determinations of body width and depth during ambulation and queuing, body ellipses can be derived. Figure 4.1 indicates a body ellipse suggested as a minimum for any design and suitable only for a tightly packed group, immobile, as in an elevator. Fruin (1970, 18) cites studies of the Otis Elevator Company showing people in elevators (with mixed occupancy) occupying approximately 1.8 square feet (0.17 m^2), which is close to the recommendation of 1.9 square feet (0.18 m^2) in figure 4.1. Figure 4.2 shows the body ellipse for mixed queues, with a 16-inch (40.6 cm) body depth, which includes an allowance of 2 inches (5 cm) for people swaying on their feet. For outdoor situations, the body ellipse will be greatly increased for umbrellas—11 square feet (1.02 m^2) for men and 4.9 square feet (0.46 m^2) for women. For design purposes, a more realistic figure of 19 to 20 inches (48–51 cm) should be used. The spacing of people in queues has been found to be very consistent.

4.1.4 The Pacing Zone

The pacing zone is the space the pedestrian needs during locomotion. This will depend on the speed of movement and the pacing length, and both of these may vary with age, sex, physique, and physical condition (and any barrier to, or incitation to, movement).

Walking on the level at a normal walking speed of 4.5 feet per second (1.37 m/sec), an average pedestrian will have a pacing distance of 2.35 feet (71.6 cm). Figure 4.3 shows the resulting pacing zone: 7.05 square feet (0.65 m^2) of space is needed, assuming a fairly comfortable body width factor of 36 inches (91.4 cm).

On stairs, the pedestrian (unless climbing the stairs two at a time, or unless the treads are very deep) in ascent and descent will always occupy two treads. Figure 4.4 shows the pacing zone of 5.5 square feet (0.51 m^2) needed for a pacing distance of 1 foot, 10 inches (55.9 cm), based on two 11-inch (28 cm) treads and a 36-inch (91.4 cm) body width factor.

4.1.5 The Sensory Zone

All of the perceptual systems acting synchronously are involved in stair cognition, approach, and traverse. An excellent discussion, and perhaps the earliest and most influential, of architecture as a modulator of human-environment relations is James Marston Fitch's 1948 book, *American Building: The Forces That Shape It.*

The auditory system informs the organism about people who are approaching but are still out of sight (for example, around the corner of the landing). The haptic system supplies information about the floor and tread and handrail surfaces. The taste-smell system is active in conditions of human proximity and to sample the air. And the basic orienting system monitors the body equilibrium. However, it is the visual

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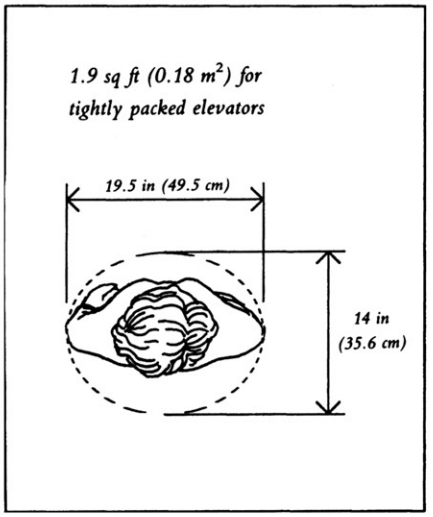
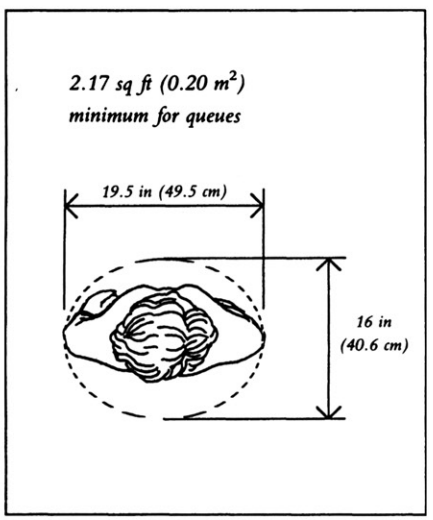
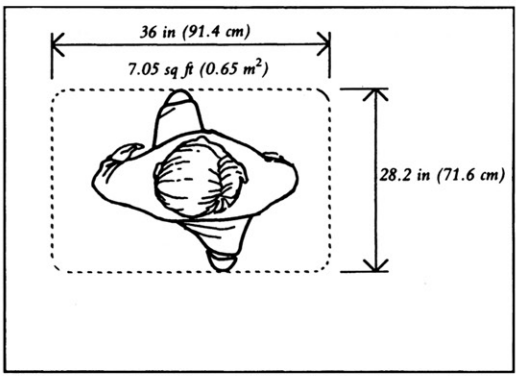


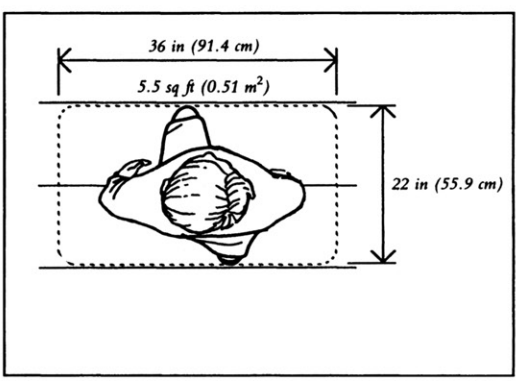
4.1 *The body ellipse, congested*



4.2 *The body ellipse, queuing*



4.3 *The pacing zone, level walking*



4.4 *The pacing zone, stairs*

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system—locomotor vision in particular—that contributes most of the information for the mapping, directing, and locomotion processes. This is confirmed by watching how slowly and carefully pedestrians with poor sight walk on the level, and particularly when negotiating stairs where the dangers of a misstep are more serious.

Using the perceptual systems to perceive, evaluate, and react to potential hazards, pedestrians maintain a bubble of space between themselves and other objects in the environment. This is done both to avoid physical conflicts and for psychocultural reasons. A conflict does not mean an actual impact; pedestrians can stop and turn with remarkable speed. A conflict is any stopping or breaking of normal walking pace due to a too close confrontation with another pedestrian (Fruin 1970, 51). This bubble of space is called the *sensory zone* because its magnitude is maintained through the monitoring performed by the sensory systems. Circumstances, however, force people to accept a bubble of space that varies in size. In crowds, they must sometimes accept conditions where there is less space than they might prefer.

At a constant normal walking speed in crowded conditions, perception and reaction time might prove to be inadequate to avoid conflicts. To compensate for this decreased clearance, pedestrians must and do reduce speed. There is a curvilinear relationship between speed and pedestrian spacing. The more the available space between pedestrians is reduced, the more they slow their pace. The faster people walk, the more space they need. On the level, pedestrian speed remains normal so long as there is about 20 to 25 square feet (1.86–2.3 m^2) per person available. As this allowance is decreased, the speed is decreased exponentially, until at about 5 to 7 square feet (0.46–0.65 m^2), normal walking ceases and is replaced by a shuffling gait. Movement ceases altogether at about 3 square feet (0.28 m^2) per person.

The proportions of the sensory zone also change as the speed is reduced because people reduce their longitudinal spacing (center to center) at a faster rate than their lateral spacing (fig. 4.5). At the limit of unobstructed movement, when the pedestrian has 20 to 25 square feet (1.86–2.32 m^2) of space, at normal walking speeds, the longitudinal spacing is about 5 feet (1.52 m). This is close to the theoretical sensory zone of 4.85 feet (1.48 m) calculated by Fruin (1970, 19) as the minimum required at normal walking speeds. He assumed a 4.5 feet (1.37 m) per second average walking speed and a pacing distance of 28 inches (71 cm).

On stairs, the sensory zone is smaller, and (horizontal component) speeds are slower because the pacing length is structured by the treads. In ascent, the pedestrians start to reduce speed significantly after the usable area is reduced below about 10 square feet (0.93 m^2) per person, and about 15 square feet (1.39 m^2) in descent. As the area is decreased further, pedestrians rapidly reduce speed until, at about (a calculated) 1.5 square feet (0.14 m^2) per person, continuous movement becomes impossible. Assuming a lateral spacing of 2 feet, 6 inches (76 cm), then 10 square feet (0.93 m^2) represents a longitudinal spacing of about 4 feet (1.22 m)—four treads—and 15 square feet (1.39 m^2) represents a spacing of about 6 feet (1.83 m) for descent—six treads. Figure 4.6 shows this spacing.

Figure 4.7 illustrates pedestrians occupying a space of 3 square feet (0.28 m^2). This

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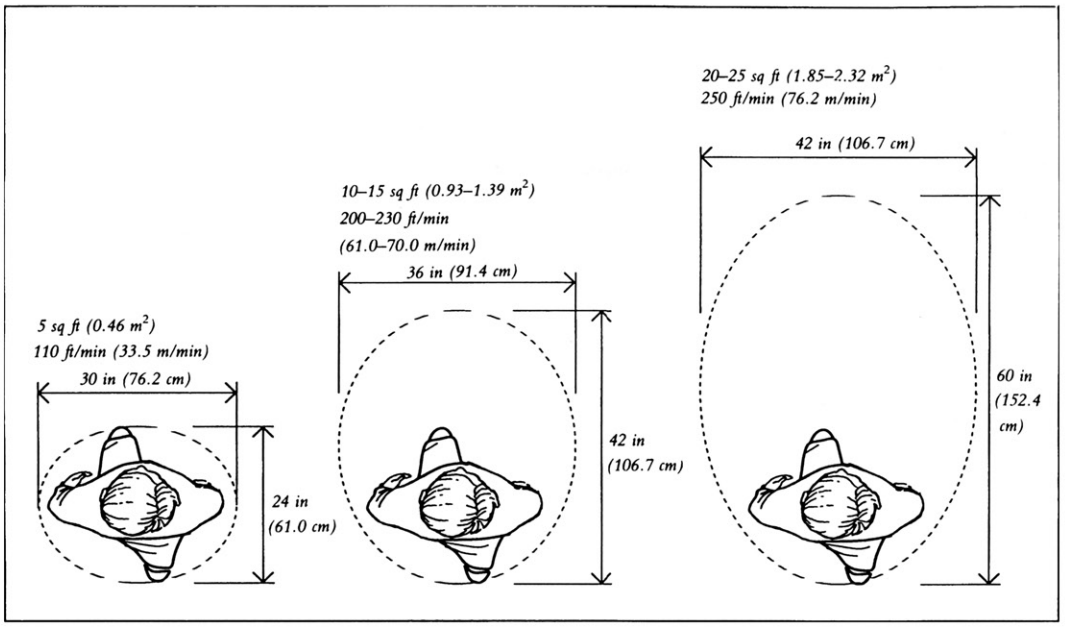

4.5 *The sensory zone, level walkways*

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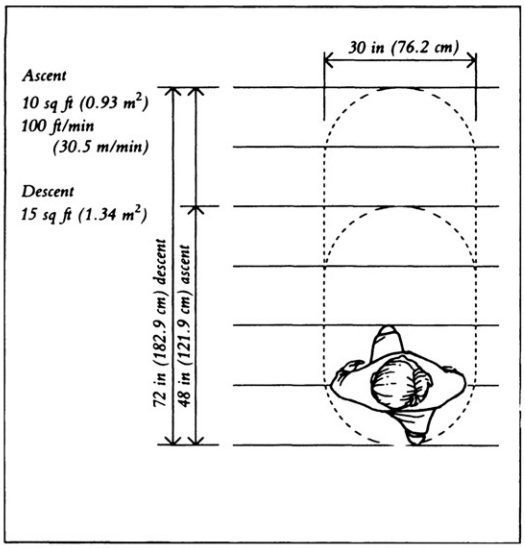
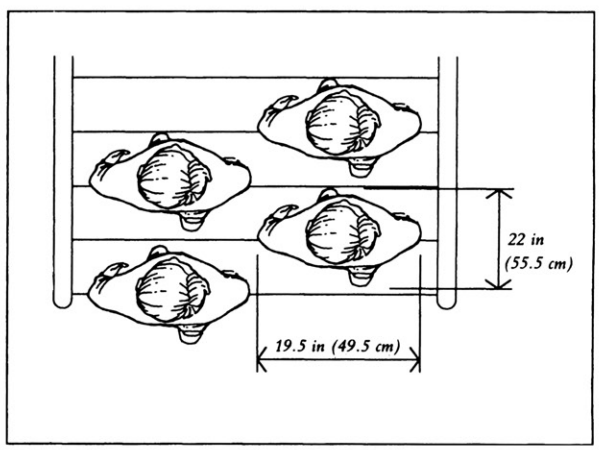
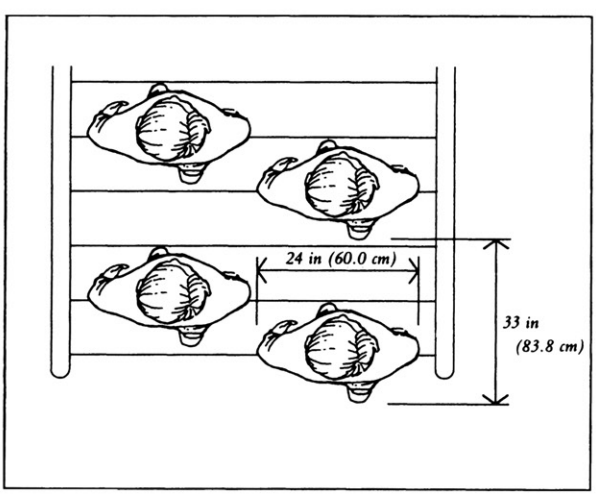


4.6 *The sensory zone, stairs*

4.7 *Stairs, theoretical maximum flow: 3 sq. ft. (0.28 m²) per person*

4.8 *Stairs, observed maximum flow: 5–6 sq. ft. (0.46–0.56 m²) per person*





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is the theoretical minimum on stairs during ambulation, the point at which the theoretical maximum flow occurs. And figure 4.8 shows a module of 5 or 6 square feet (0.46–0.56 m^2), which is the smallest area actually observed, using an assumed width of 24 inches (61 cm) for highly constrained movement.

4.1.6 The Buffer Zone

The buffer zone, unlike the sensory zone, does not exist primarily to prevent physical collisions but to maintain an acceptable distance, a personal space that is appropriate to the human relationship being encountered. This distance is the well-known hidden dimension that Edward T. Hall (1969) and others have studied in order to develop a theoretical construct, the science of proxemics. *Personal distance* is the phrase Hediger coined to designate the distance consistently separating noncontact species.

Hall identified four distance zones within which certain types of interpersonal relationships are acceptable, and others not. *Intimate distance,* less than 18 inches (45.7 cm)—3 square feet (0.28 m^2) per person—is appropriate for body contact sports and intimate personal contacts. It is inappropriate for casual relationships and is tolerated by Americans only under extremely crowded conditions. *Personal distance,* from 1½ to 4 feet (0.5–1.22 m), or 3 to 13 square feet (0.28–1.2 m^2), is an appropriate distance for a husband and wife but not for impersonal transactions. *Social distance,* 4 to 12 feet (1.22–3.66 m), or 13 to 110 square feet (1.2–10.2 m^2), is suitable for impersonal relationships and social contacts. Finally, at a *public distance* of 12 or more feet (3.66 m), exchanges will no longer be intimate or social but public. This is the distance between actors, preachers, and politicians and their audiences.

These distances are by no means fixed, and they vary according to cultural, psychological, and environmental factors. Latins may accept closer distances than Americans. Aggressive people may demand more. And, of course, crowding may make these preferences impossible. However, when these territorial zones are violated, whether voluntarily or not, the psychological tensions that are produced generate defensive patterns of behavior: changes of direction or movement, a deliberate aloofness, immobility and muscular tension, or even violence.

The buffer zone is in reality not a sphere but a contour, because the spatial demands directly in front of the face are usually larger than those at the back (Goffman 1971, 30). The outline surface of these contours is normally soft and plastic and reasonably adaptable to circumstances. The organism expands, contracts, and modifies the shape of the bubble or, under conditions of anger or tension, hardens, regularizes, and sensitizes the surface so that it becomes a defensive perimeter to be penetrated at some risk.

There is little doubt that these buffer zones act to moderate or even dominate the voluntary spacing chosen by pedestrians. Commuters in queues, for example, have been found to space themselves about 20 inches (51 cm) apart; the need to show that one is part of the queue impels people to locate within the personal distance (albeit in an impersonal fashion) but not within the much more sacrosanct intimate distance.

People in moving queues on the level or on stairs may well be adjusting their spac-

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ing to maintain a personal buffer zone. On stairs, under conditions of free flow, pedestrians adopt a minimum longitudinal spacing of about 4 feet (1.22 m), which corresponds to the lower end of the scale of social distance. Because the horizontal component of speed of ambulation on stairs is restricted by the stair's geometry and is not great, it may be that this spacing is chosen more as a personal buffer than as a sensory zone to avoid conflicts.

4.1.7 Summary

The body ellipse and the pacing zone provide information on the absolute minimum space needed. The sensory and buffer zones are important for stair design purposes, for it is in relation to them that a stair will be safe and comfortable.

1. A stair width of 29 inches (73.7 cm) between walls is a minimum for public places, and 38 inches (96.5 cm) is recommended for comfort.

2. For side-by-side and passing movements, a stair between walls should be not less than 56 inches (1.42 m), and 69 inches (1.75 m) is recommended for comfort.

3. For ambulation on stairs, the pacing zone requirements mandate a design module minimum of 5.5 square feet (0.51 m^2)—36-inch width by 22 inches (91.4 × 55.9 cm). This is close to the observed spacing that people take up when the stair flow is at a maximum.

4. For free, unobstructed flow at a normal speed of about 100 feet (30.5 m) per minute for ascent and 120 feet (36.6 m) per minute for descent, a pedestrian requires about 10 square feet (0.93 m^2)—30-inch width by 48 inches (0.76 × 1.22 m)—for ascent and 15 square feet (1.39 m^2)—30-inch width by 72 inches (0.76 × 1.83 m)—for descent. These dimensions also correspond to the lower end of the social distance required to provide a comfortable buffer zone.

4.2 Walkway Capacity

Until fairly recently, the design precepts that govern the capacity of ramps, walkways, and stairs have been grounded more on informed judgment than on theoretical constructs. Over the last two decades, however, pedestrian traffic design has begun to emerge as a discipline.

In any pedestrian movement system, the component parts are interlocked and dependent on each other. The walkway capacity is controlled by the stair that terminates it; the stair's capacity is affected by its location. For this reason, the capacity of each of these components must be considered, as well as the interaction between them.

The relationships of rates of pedestrian flow, pedestrian space requirements, and speeds of movement have been studied by several researchers (Oeding 1966, 66; Older 1968, 160–163; Navin and Wheeler 1969, 30–36; Tregenza 1976; Predtechenskii and Milinskii 1969; Pauls 1982; Pushkarev and Zupan 1975).

4.2.1 Flow Equations for Pedestrian Traffic

Derived from an analogy to fluid flow, the generalized equation of traffic flow is:

Flow = Speed × Density,

where, for pedestrian planning, flow is the number of pedestrians per minute per foot (or meter) width of walkway (PPM) and density is the number of pedestrians per square foot (or m^2). This equation assumes a relatively uniform flow; it may not apply

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to situations where strollers and commuters mix. Expressing density in this way is conceptually clumsy because it produces results in terms of fractions of a pedestrian. The reciprocal of density—space, square feet (m^2) per pedestrian—is easier to visualize and changes the equation to:

$$\text{Flow} = \frac{\text{Speed}}{\text{Space}}$$

or $\quad \text{Speed} = \text{Flow} \times \text{Space}.$

(In all the observations discussed, except when stated, flow is bidirectional.) The resultant speed-flow curves are parabolic and can be expressed as quadratic equations:

$$\text{Speed} = \frac{A \pm \sqrt{A^2 - 4B\text{Flow}}}{2}.$$

The constant A is the (theoretical) speed of the pedestrians under conditions of free flow and unlimited space; B/A is the (theoretical) minimum space at which point action is so constricted that movement stops. These figures can be obtained by plotting speed against density—a lineal relationship, where A is the y intercept and B is the slope:

$$\text{Speed} = A - B \times \text{Density}.$$

Dividing the value for the speed, at any point on the parabolic curves, by the flow at that point gives the amount of space available per pedestrian. The flow can then be expressed by the equation:

$$\text{Flow} = \frac{A\text{Space} - B}{\text{Space}^2}.$$

4.2.2 Level Walkway Flow, Space, and Speed Patterns

Maximum flow on level walkways occurs when pedestrians have between 5.2 and 9.1 square feet (0.48 and 0.85 m^2) of space. When the space available drops below 5 square feet (0.46 m^2) per person, the speed of movement and the rate of flow decline rapidly until, at a space allocation of between 2 and 4 square feet (0.19–0.37 m^2) per person, the traffic comes to a standstill (fig. 4.9; from Fruin 1987). On the other hand, increasing pedestrian space above 9 square feet (0.84 m^2) decreases the capacity of the walkway progressively. At about 40 square feet (3.7 m^2) per pedestrian, for example, the flow rate is only 24 to 32 percent of the maximum.

It has been observed that 99.7 percent of walkers at Pennsylvania Station in New York, under free flow conditions, select speeds between 400 feet (122 m) per minute—4.5 mph (7.24 kmph), on the verge of a run—and 145 feet (44.2 m) per minute—1.6 mph (2.57 kmph), on the verge of shuffling (Fruin 1970, 39). An average walking speed is between 250 and 300 feet (76–91 m) per minute, with women about 5 percent slower than men. The speed is affected by such factors as trip purpose, time of day, and ambient temperatures, among others. When the space available drops below 40 to 50 square feet (3.7–4.6 m^2) per pedestrian, normal walking speed is affected. Below 25 square feet (2.3 m^2) per pedestrian, normal walking speed is reduced progressively as the space is reduced.

4.2.3 Walkway Conflicts

Besides speed reduction, several other indications of incipient congestion can be noted: route conflicts, overtaking constraints, reverse flow, and bulk arrivals. Conflicts are inevitable at areas of less than 15 square feet (1.4 m^2) per person, but as the area increases, conflicts decrease until at about 35 square feet (3.25 m^2) per pedes-

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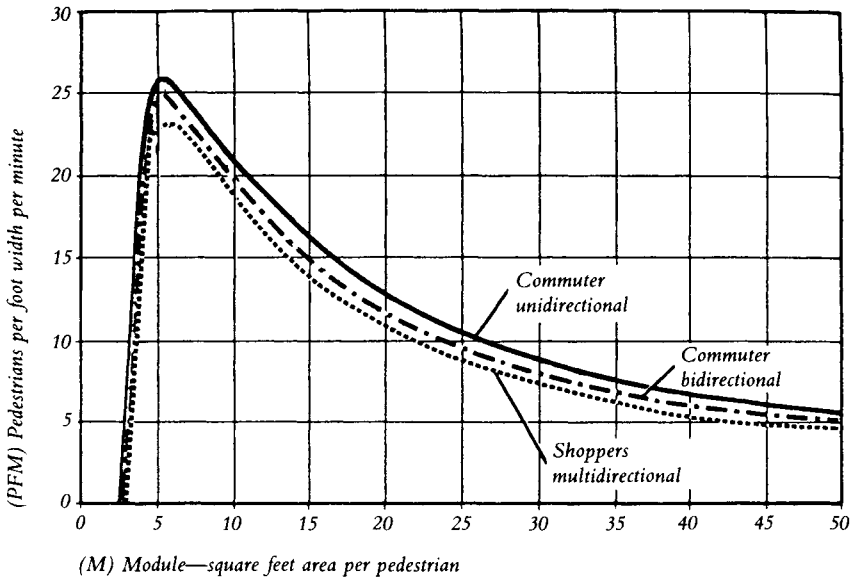

4.9 *Pedestrian flow and area on walkways, reprinted from Fruin (1987), 44*

trian, the probability of conflict decreases rapidly to zero.

4.2.4 Overtaking on Walkways

Above 36 square feet (3.3 m^2) per person, overtaking is reasonably easy, but between 36 and 18 square feet (3.3 and 1.7 m^2) per person, overtaking becomes increasingly difficult, and below 18 square feet (1.7 m^2) per person, physical contact during overtaking is unavoidable.

4.2.5 Reverse Flow on Walkways

Reverse flow (pedestrian movement in the opposite direction to the predominant flow) does not start to reduce total (bidirectional) flow significantly until the area per person is reduced below about 10 square feet (0.93 m^2). Flow is affected more significantly as directional imbalance increases. For a bidirectional proportion of 25 percent/75 percent, capacity is reduced by less than 10 percent; for a 10 percent/90 percent distribution, capacity is reduced by 14.5 percent at 10 square feet (0.93 m^2) per person. None of the studies, however, is specific about the effect of walkway width on reverse flow.

4.2.6 Platoons

Studies of bulk arrival situations, or platoons as they are called, show that during these conditions, average flow rates increase significantly. Subway trains and traffic lights release people in platoons, but platoons can also be generated spontaneously as slower walkers hold up faster pedestrians. Even for average flow rates, measured over periods as short as 1 minute, conclusions on pedestrian flow can be misleading, for platoons have been found to have durations of less than 50 seconds, and during these periods, the flow rate has

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been found to be up to two and a half times as great as the average flow rate.

From limited observations, it can be concluded that the relationship between platoon flow and average flow can be expressed by the equation (where the flows are expressed in pedestrians per minute per foot of walkway):

Platoon flow = 4 + Average flow.

This means, for example, that an average flow rate of 6 to 10 pedestrians per minute per foot (20 to 33 per meter) of walkway—"constrained" movement—may actually conceal a platoon of 10 to 13 pedestrians per minute per foot (33 to 43 per meter), which is "congested" movement.

The research on platoons has been exploratory and limited to a few types of locations and walkways; further studies are necessary relating to various types and dimensions of locations at different times of the day.

4.2.7 Recommended Levels of Service for Walkways

The level-of-service concept was developed by traffic engineers to indicate the levels of performance that could be expected to result from flow design choices. Table 4.4 is an elaboration of one generated by Pushkarev and Zupan (1975). It summarizes pedestrian flow characteristics into eight levels of service, dependent on the average area allowed per pedestrian.

4.3 Ramp and Stair Flow and Capacity

4.3.1 Ramp Capacity

In comparison to walkways, research into ramp and stairway flow and capacity has been sparse and limited in scope. However, pedestrian flow on ramps, within certain gradient limits, is similar to that on level walkways, and ramps slow the flow of mass pedestrian movement to a much smaller degree than stairs. In ascent, on grades up to about 3 degrees (5 percent or 1:20), there are "no statistically significant differences in walking speed due to grades of up to six per cent, according to a survey of walking speeds by age, sex, and grade categories . . . [and] a controlled study of soldiers walking on a variable grade treadmill revealed that an increase in positive treadmill grade, from 5% to 10% [3–6 degrees, 1:20 to 1:10], decreased walking speeds by 11.5%" (Fruin 1970, 41).

Pedestrian speed on level walkways (Turner and Collins 1981) ranges from about 140 to 467 feet (43–142 m) per minute; 250 feet (76 m) per minute is the median. The range of average speeds on ramps is within the same range as on level walkways. However, the range of average speeds on stairs is only about 130 to 150 feet (40–46 m) per minute. Within the range of normal use, that is, at grades of less than 15 percent, it is probable that the capacity of ramps does not differ appreciably from level walkways. (This conclusion is supported by the work of Turner and Collins from their observations of ramps in Baltimore.) Ambulation speed is, however, reduced to some extent (25 percent reduction in horizontal speed at a 20 percent grade). In uphill movement, this decrease in speed is compensated for by a closer spacing; downhill, when speed is increased, the spacing is increased.

4.3.2 Stairway Capacity

Fruin's (1970) is the most rigorous and fully documented stair flow study, but he examined only two stairs and these had the

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TABLE 4.4

Levels of Pedestrian Density in Movement on the Level

Average Area per Person, sq. ft. (m^2)	*Characteristics*
Level 1:	*Flow: erratic, on verge of complete stoppage*
2 to 5 (0.2–0.5)	*Average speed: shuffling only, 0–100 ft./min. (0–30 m/min.)*
	Choice of speed: none, movement only with the crowd
	Crossing or reverse movement: impossible
	Conflicts: physical contact unavoidable
	Passing: impossible
Level 2:	*Flow: 23–25 PPM/ft. (75–82 PPM/m), a maximum in traffic stream under pressure*[a]
5 to 7 (0.5–0.7)	*Average speed: mostly shuffling, 100–180 ft./min. (30–55 m/min.)*
	Choice of speed: none, movement only with the crowd
	Crossing or reverse movement: most difficult
	Conflicts: physical contact probable, conflicts unavoidable
	Passing: impossible
Level 3:	*Flow: 19–23 PPM/ft. (62–75 PPM/m), attains a maximum in relaxed traffic streams*
7 to 11 (0.7–1.0)	*Average speed: about 70 percent of free flow, 180–200 ft./min. (55–61 m/min.)*
	Choice of speed: practically none
	Crossing or reverse movement: severely restricted, with conflicts
	Conflicts: physical contact probable, conflicts unavoidable
	Passing: impossible
Level 4:	*Flow: 15–19 PPM/ft. (49–62 PPM/m), 65–80 percent of maximum capacity*
11 to 15 (1.0–1.4)	*Average speed: about 75 percent of free flow, 200–240 ft./min. (61–73 m/min.)*
	Choice of speed: restricted, constant adjustments of gait needed
	Crossing or reverse movement: severely restricted, with conflicts
	Conflicts: unavoidable
	Passing: rarely possible without touching
Level 5:	*Flow: 12–15 PPM/ft. (39–49 PPM/m), 56–70 percent of maximum capacity*
15 to 18 (1.4–1.7)	*Average speed: about 80 percent of free flow, 240–270 ft./min. (73–82 m/min.)*
	Choice of speed: restricted except for slow walkers
	Crossing or reverse movement: restricted, with conflicts
	Conflicts: probably high
	Passing: rarely possible without touching
Level 6:	*Flow: 10–12 PPM/ft. (33–39 PPM/m), roughly 50 percent of maximum capacity*
18 to 25 (1.7–2.3)	*Average speed: more than 80 percent of free flow, 270–290 ft./min. (82–88 m/min.)*

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	Choice of speed: unless stream similar, restricted by bunching *Crossing or reverse movement: possible, with conflicts* *Conflicts: probably high* *Passing: difficult without abrupt maneuvers*
Level 7: *25 to 40 (2.3–3.7)*	*Flow: 7–10 PPM/ft. (20–33 PPM/m), roughly one-third of maximum capacity* *Average speed: nearly free flow, 290–310 ft./min. (88–94 m/min.)* *Choice of speed: occasionally impeded* *Crossing or reverse movement: possible with occasional conflicts* *Conflicts: about 50 percent probability* *Passing: possible, but with interference*
Level 8 *Over 40 (over 3.7)*	*Flow: one-fifth maximum capacity or less* *Average speed: virtually as chosen* *Choice of speed: virtually unrestricted* *Crossing or reverse movement: free* *Conflicts: maneuvering needed to avoid conflicts* *Passing: free, with some maneuvering*

[a]*PPM/ft.: pedestrians per minute per foot width of walkway; PPM/m: pedestrians per minute per meter width of walkway.*
Source: Pushkarev and Zupan (1975) with flow and speed figures derived from Fruin (1987).

same riser and tread dimensions, 7 by 11 inches (17.8 by 27.9 cm). To gather his data, Fruin photographed ascending commuter traffic in the Manhattan terminal of the Staten Island Ferry and ascending and descending traffic at Shea Stadium. The equations that follow are based on the curve of these results. The flow-space equations of stair flow for ascending stairs are:

$$\text{Flow} = \frac{111 \times \text{Space} - 162}{\text{Space}^2}$$

$$\text{Speed} = \frac{111 \times \text{Space} - 162}{\text{Space}}$$

where: Flow = pedestrians per minute per foot width,
Speed = feet per minute,
Space = square feet per pedestrian.

For descending stairs, the equations are:

$$\text{Flow} = \frac{128 \times \text{Space} - 206}{\text{Space}^2}$$

$$\text{Speed} = \frac{128 \times \text{Space} - 206}{\text{Space}}$$

Note that measurements for flow must be based on the effective width of the stair. This depends on the presence of adjoining walls and handrails. The effective width will be the actual width minus about 6 inches (15.2 cm) where there is an adjoining wall and minus about 3½ inches (8.9 cm) from the centerline of a graspable handrail. For example, in a stair that is 54 inches (1.4 m) wide and has a wall on one side and a graspable handrail on the other, the center of the handrail is 4 inches (10.2 cm) from the outer edge of the stair. The effective width will be:

54 − 6 − 4 − 3.5 = 40.5 inches (1.03 m).

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Stairway movement, flow, and capacity are markedly different from those on level and inclined walkways. For normal, free, unobstructed speed, much less room is necessary on stairs—11 square feet (1.02 m^2) per pedestrian for ascent and 15 square feet (1.39 m^2) for descent—than on walkways—about 35 square feet (3.25 m^2).

Because the horizontal component of pedestrian speed is much less on stairs, even in descent, than on level walkways, free flow is reached in ascent at a speed of about 100 feet (30 m) per minute and 120 feet (37 m) per minute in descent (and this would be a shuffling speed on a level walkway), compared to around 300 feet (91 m) per minute for walking on the level in free flow.

Because of the reduced speed, both the theoretical and observed maximum capacity of stairs is less than for walkways of similar dimensions. Theoretically this means that a stair in a corridor should be about a third wider than the corridor. However, if the corridor and stair are sized to allow a flow of about 15 pedestrians per minute per foot (49 per minute per meter) width, there is no need to increase the stair width (unless to allow for extreme, unpredictable events—a sensible precaution where capacities are unpredictable and where the stair might become a bottleneck).

The theoretical maximum unidirectional flow on stairs from the equations is 18.9 people per minute per foot (62 per meter) width—16.0 observed in the up direction and 20.0 descending—compared to 23 to 26 people per minute per foot (75 to 85 per minute per meter) width calculated for walkways (26 to 48 observed). This suggests that different design standards should be used for up stairs and down stairs and that a proposed stair design should be tested for its capacity in each direction (figs. 4.10 and 4.11) (Fruin 1987).

The maximum unidirectional ascent flow of young and middle-aged men leaving a factory, as studied by Oeding (1966), was 16.7 pedestrians per foot (55 per meter) width of stair. Pushkarev and Zupan (1975), after studying two subway stairways, found the maximum ascending flow to be 16.2 pedestrians per foot (53 per meter) of stair, so there is considerable agreement on maximum flow in ascent. Pushkarev and Zupan, however, found that these volumes could be achieved only where there was a queue waiting to use the stair. The queue "force-fed" the stair. Without queues, the maximum unidirectional flow in the first study dropped to between 12.2 and 13.7 persons per foot (40–45 per meter) per minute (10 square feet per person—0.93 m^2 per person). Furthermore, on some steeper stairways in a downtown location, Oeding (1966) found that the maximum capacity was 6.0 to 7.6 persons per minute per foot (19.7–24.9 per meter) width at 15.5 and 20.0 square feet (1.4 and 1.86 m^2) per person and speeds of about 120 feet (36.6 m) per minute. Under these conditions, pedestrian movement was considerably restricted, and passing was impossible. Without queues, in the other study, the figure dropped to 11.2 to 12.0 persons per foot (37–39 per meter) per minute, depending on whether there was light reverse flow or none.

The "force-fed" stair is not a good solution; it will slow the traffic on the walkway to a speed that can deteriorate into a stop-and-go movement (unsafe on stairs) and will necessitate a queuing area. It could

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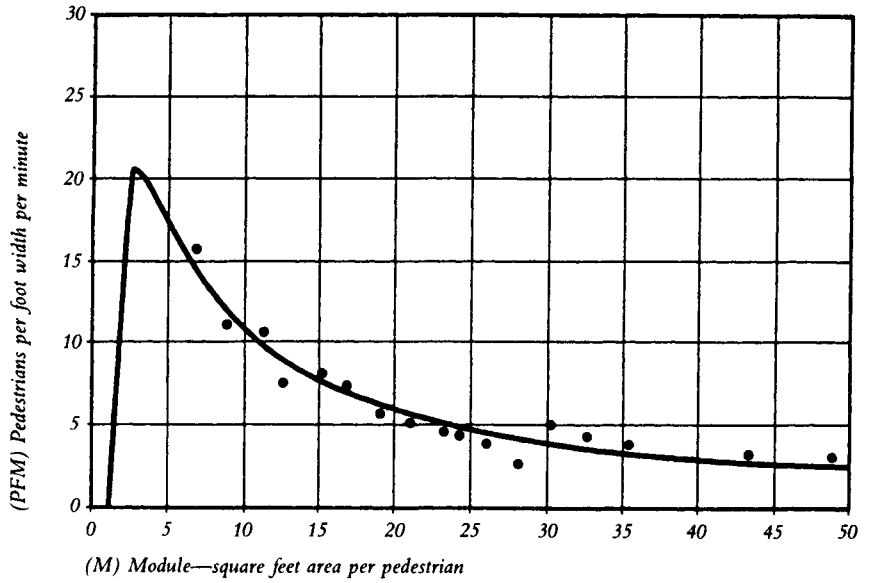
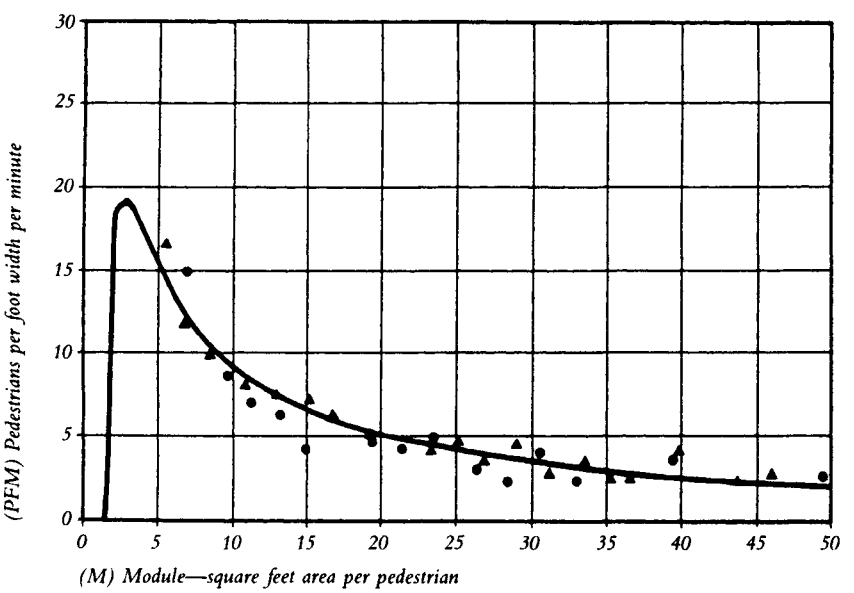


4.10 *Pedestrian flow and area on stairs, descent, reprinted from Fruin (1987), 60*



4.11 *Pedestrian flow and area on stairs, ascent, reprinted from Fruin (1987), 60*

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also be dangerous in conditions of panic.

From the results of observed maximum unidirectional flow with no queuing, 12.0 people per minute per foot (39 per meter) width, and using the ascent formula pedestrians are unwilling to use a stair unless they have at least 7.4 square feet (0.69 m^2) per person—except where they are under the psychological (and even physical) pressures from being at the head of queue.

4.3.3 Reverse Flow on Stairs

Reverse flow appears to affect stairways much more than walkways, probably because of the limitations on agility imposed by stairs; however, these conclusions may reflect the fact that most stair flow studies have been carried out using comparatively narrow stairways (Pushkarev and Zupan used stairs that were 5 feet, 8 inches and 4 feet, 8 inches in width). If a stair is only wide enough for two people side by side, at even moderate rates of flow, the capacity may be halved by a reverse flow of only a very small number of people, depending on the length of the stair.

A reverse flow of one to three people (per upward platoon of about fifty-six people) is a light reverse flow. A heavy reverse flow is more than three. With no reverse flow, the observed maximum flow without queuing is 12.0 pedestrians per minute per foot (39 per minute per meter). With light reverse flow, this drops to 11.2 pedestrians per minute per foot (37 per minute per meter). With heavy reverse flow, queues will still form at a flow rate of 7.6 pedestrians per minute per foot (25 per minute per meter).

Where reverse flow is likely to be a major factor in producing stair congestion, several solutions are available: more stairs can be provided, the stairs can be made wider and channelized, or stairs can be designated by signs as unidirectional. The signs and the stair direction can be switched to suit the exigencies of the traffic conditions, particularly to suit the directional flow proportions of rush hour traffic. Alternatively, stairs can be located so that pedestrians will choose to use the stair unidirectionally. Pedestrians look for convenience and will usually choose the first available stair. With careful planning, it can be arranged that the first available stair will not be as convenient for traffic moving in the other direction.

4.3.4 Recommended Levels of Service for Stairs

Table 4.5 summarizes pedestrian flow characteristics on stairs into six levels of service. Fruin recommended the use of no levels higher than E. However, to avoid queues forming, level E should be avoided also, and level D used with discretion.

4.4 Conclusions

The flow of traffic on level walkways, ramps, and stairs can be described mathematically, based on both theoretical constructs and field observation. Pedestrian flow is primarily related to the speed and spatial demands of the pedestrians, and, from these, the capacity of the route can be gauged. Other factors act to modify, or are modified by, the flow of the pedestrians—directional conflicts, overtaking movements, reverse flow, and bulk arrivals or platoons—but the effect of these can also be taken into account. In addition to the factors touched on in this chapter, stair capacity is also affected by the stair's layout. Only straight flight stair capacity has been discussed. Composite and helical stairs introduce quite different flow patterns and

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user habits, and even the capacity of straight flight stairs may be decreased significantly if the stair is poorly located or if the approaches encourage conflicts, confused responses, or erratic movement routes on the stair. Stair layout and vicinage as they affect flow patterns are investigated in the next chapter.

Recommendations for the design of walkway and stair capacity have been tabulated (tables 4.4 and 4.5) using the level-of-service concept.

TABLE 4.5

Levels of Pedestrian Density in Movement on Stairs

Average Area per Person, sq. ft. (m^2)	*Characteristics*
Level F:	*Flow: up to 20 PPM/ft. (66 PPM/m), flow attains a maximum, but is erratic*
Less than 4 (0.37)	*with frequent stoppages and verges on complete breakdown*[a]
	Average horizontal speed: shuffling, 0–70 ft./min (0–21 m/min)
	Choice of speed: none
	Passing: impossible
	Queuing at stair entrance: yes
Level E:	*Flow: 13–17 PPM/ft. (43–56 PPM/m), intermittent stoppages*
4 to 7 (0.37–0.65)	*Average horizontal speed: 70–90 ft./min (21–27 m/min)*
	Choice of speed: none
	Passing: impossible
	Queuing at stair entrance: yes
Level D:	*Flow: 10–13 PPM/ft. (33–43 PPM/m)*
7 to 10 (0.65–0.93)	*Average horizontal speed: 90–95 ft./min (27–29 m/min)*
	Choice of speed: restricted
	Passing: impossible
	Queuing at stair entrance: some at higher flow level
Level C:	*Flow: 7–10 PPM/ft. (23–33 PPM/m)*
10 to 15 (0.93–1.4)	*Average horizontal speed: 95–100 ft./min. (29–30 m/min)*
	Choice of speed: restricted
	Passing: impossible
	Queuing at stair entrance: none
Level B:	*Flow: 5–7 PPM/ft. (16–23 PPM/m)*
15 to 20 (1.4–1.9)	*Average horizontal speed: 100 ft./min. (30 m/min)*
	Choice of speed: freely selected
	Passing: restricted
	Queuing at stair entrance: none
Level A:	*Flow: 5 or less PPM/ft. (16 PPM/m or less)*
More than 20 (1.9)	*Average horizontal speed: 100 ft./min. (30 m/min)*
	Choice of speed: freely selected
	Passing: at will
	Queuing at stair entrance: none

[a] *PPM/ft.: pedestrians per minute per foot width of walkway; PPM/m: pedestrians per minute per meter width of walkway*

Source: Fruin (1987).

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5 BEHAVIOR ON STAIRS

Undoubtedly a stair acts on me as a compelling stimulus: . . . The stair stimulates me to go up, *even when, stumbling over the first step in the dark, I cannot see it. There are, on the other hand, two factors that cannot be left out of account here, concerning the fact that in all probability I would be going up the stair on the basis of knowing that that is what a stair is for. First, in going up such a structure at some time in the past, I* learn *to go up, and thus I learn to respond to the stimulus; otherwise, the stimulus alone might well fail to produce the expected response. Second, once I have learned that the stair stimulates me to go up (and permits me to pass from one level to another), from that moment on I* recognize *in a stair the stimulus presented and the possibility that is offered of a fulfillment of function.*

So from the moment I recognize it as a stair and subsume it under the general concept of "stair," the individual stairway communicates to me the function it permits; and it communicates this to such an extent that from the type of stair (grand marble staircase, winding stairway, steep and narrow stair, moving staircase) I see, perhaps first of all, whether it would be relatively easy to go up or an effort. (Eco 1980, 14–15)

This chapter discusses some of the ways people act and react as they use stairs, and, in particular, how these are reflected in their movement patterns, and, conversely, how stair design and vicinage may affect

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these behavioral patterns. The primary question raised is whether there is continuity of behavior—usually regular, consistent, and identifiable ways in which people act and respond (behaviorally) to a particular stair design and situation.

An affirmative answer to the primary question leads to a second series of questions. Is this behavior generalized? Are there behavioral patterns that persist from stair to stair? Because every stair is to some extent different, one would expect to find, at best, some consistent behavior, probably to the extent that parts of the comparable stairs are identical in shape, vicinage, and traffic. Is there any consistency?

If there is generalized, persistent, and largely consistent behavior, is it identifiable and predictable? Can the strengths of the associations between these regular actions and the component parts of stairs, to which they respond, be measured?

The next issue is one of experiential congruence: how well do various (typical) stair layouts accommodate the behavior for which they are planned? Does the design increase or minimize the occurrence of turbulence and conflicts, of people bumping into one another, or at least being forced to take rapid avoiding action? Do some stair layouts fit the human responses and the environmental forces deployed in the immediate spatial surroundings better than the alternatives? Do some stairs induce unsafe behavior?

The few studies of human behavior on stairs have focused on two general areas: the routes that people take on stairs and the way that people react to the stair and its surroundings. Several questions have been considered:

- What routes do people take on stairs?
- Are these routes affected by the stair layout?
- Are there stair layouts that reinforce consistent flow patterns?
- Are the routes affected by where people have come from or are going to?
- Are route choices affected by crowding?
- Do people usually keep to the right (in the United States)?
- If people keep to the right, what induces violations of the rule?

5.1 Stair Erosion

One way to examine behavior on stairs is to examine the evidence of people's passing, the patterns eroded into stairs and handrails. Just as the spoor of animals is decipherable and is descriptive of their habits and the routes they choose to take, so are the erosion patterns of people (fig. 5.1). Erosion provides the evidence that behavior is largely consistent. Not everyone may exhibit the same behavior, but many do.

The fog had probably just cleared. The singular Sherlock Holmes had been reunited with his old friend, Dr. Watson (after one of Watson's marriages), and both walked to Watson's newly acquired office. The practice was located in a duplex of two physician's suites, both of which had been for sale. No doubt sucking on his calabash, Holmes summarily told Watson that he had made a wise choice in purchasing the practice that he did, rather than the one on the other side of the duplex. The data? The steps were more worn on Watson's side than on his competitor's. (Webb et al. 1970, 35)

Without producing his magnifying glass, Holmes could possibly have told Watson more about his patients—from which direction they came (wealthy Mayfair or

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5.1 *Erosion of the stairs in Wells Cathedral*

poor Paddington) or whether they were habitually law abiding (did they observe the rules of the road on the stair), for example. The pattern worn into a staircase is as much declarative of how it has been used as how often.

The pattern of wear on the treads is the pattern of general human behavior and exists because people choose a path to ascend or descend a staircase. They make their choices with as much deliberation and consistency as they evince when using any other part of the physical environment. The path eroded into a staircase is no different in this way from a track trodden through the undergrowth of a copse or across a college lawn. People choose a route for the advantages they gain or the obstacles they avoid. The route is quicker, safer, more beautiful, more convenient, or more comfortable. The outcome of the movement through the environment is a recognizable path rather than a randomly eroded surface because of the continuity of behavior.

Stair erosion is a petrified (if dynamic) indicator of people's responses to stairs. If the causes of, and reasons for, erosion are understood, this provides at least a partial understanding of behavioral responses to stairs and an indication from which a proemial system of principles can be hypothesized. It gives a tool for translating the evidence of behavior under a very specific set of environmental conditions. There is, then, always the possibility that some aspects of that behavior might turn out to be sufficiently constant in time and situation as to be predictable. These aspects can assist in the development of a system of principles.

From studying the erosion patterns, we can discover how a staircase has been

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used—not by individuals, of course, but by the flow of the main stream of pedestrians over time. From these observations, a reasonable hypothesis can be constructed to explain what is observed and why the stair was used in this way.

Confining erosion observations to the treads and risers and excluding clues from handrails, markings on adjacent walls, and so on, typically, there are two main erosion configurations. These result from stair ascent and descent. A third type is apparent where the tread configuration has been radically eaten away as a result of the combined ascent and descent actions. All of these erosion patterns occur naturally in response to the mechanical and frictional forces exerted by the motion of many shoes. The resultant damage reflects the way that the actions employed in ascent differ from those of descent.

All of the descriptions of movement and stair erosion that follow describe conditions for normal stair ratios. The pattern for a monumental stair, a ship's companionway, or any other stair does not differ in principle, but the changed geometry changes the location and extent of the wear.

5.1.1 Erosion of Ascent

In ascent, the lower leg swings forward and upward, passing the foot on the next tread. Then the foot is lowered onto the next-but-one tread. At normal climbing speeds and for the accepted range of tread-riser ratios, the foot is positioned so that some or all of its surface fits on the stair tread. This is a generalization; stair climbing is as individual an activity as walking, so the description aims to discuss the average motion that produces erosion.

At contact, the leading foot still retains a degree of forward motion, which is checked by the frictional connection between step and foot (fig. 5.2). Often both the heel and toe make contact more or less simultaneously, so most of the resultant frictional erosion takes place in the central part of the tread, between the nosing and the riser. The location of the erosion is conditioned by the depth of the tread. The leg then tilts forward about the ankle. The body's weight rolls forward until the weight transfer onto the other foot on the next step up has been completed. While this is happening and the forward foot is lifting the body upward, the lower foot is pivoting forward onto the toes (fig. 5.2). It is exerting a backward thrust, which is resisted by the surface of the tread.

This time, erosion is found on the tread in the area where the toes have been. This forms a concave erosion pattern that tends toward that shown on the treads in figure 5.2. The actual position of the area of maximum wear due to ascent depends on the dimension of the tread. It appears closer to the nosing as the tread depth decreases.

5.1.2 Erosion of Descent

Stair descent produces quite a different pattern. As the foot is lowered onto the next step, the toes are pointed down to some degree (fig. 5.3). The foot touches the step, usually toes first, and the body's weight is transferred to this forward leg. Depending on the tread size and the speed of descent, the foot may overlap the nosing slightly, or may be positioned within the tread. In either event, the forward impetus of the foot is resisted by the frictional resistance of the front of the tread at the nosing. In due course, the other foot swings past, and it is set down on the next step. The body weight is transferred to it. The rear foot pivots on its toes as the trailing leg bends

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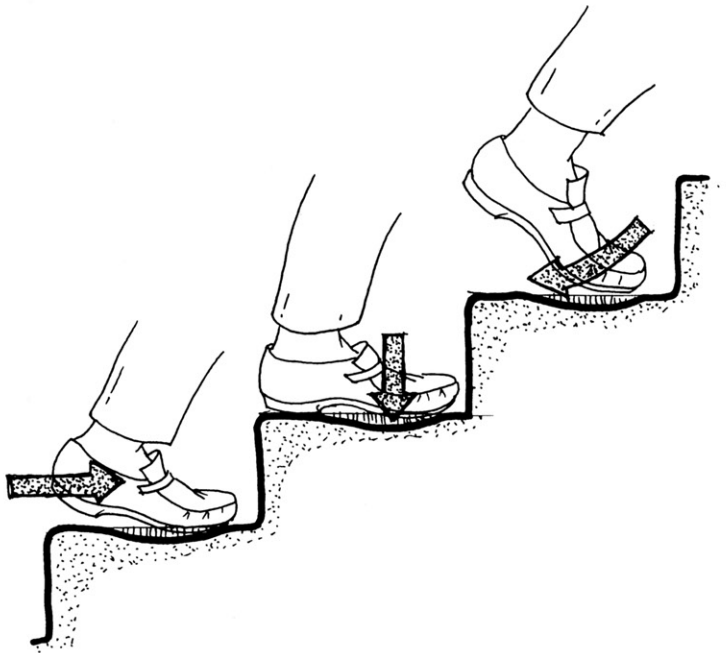
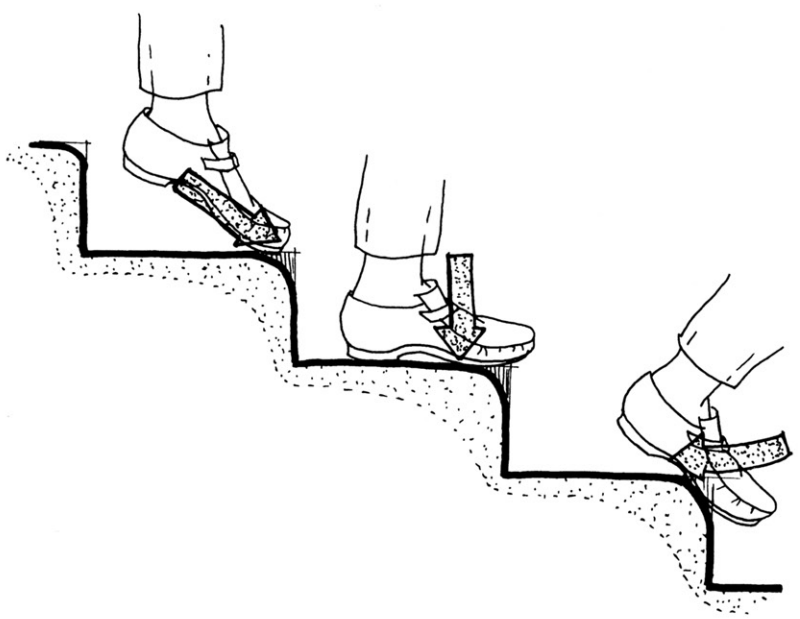


5.2 *The erosion of ascent*



5.3 *The erosion of descent*

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at the knee. These actions erode the tread at, or very close to, the nosing.

In descent, therefore, both initial contact erosion and the later erosion from the rear foot act principally against the front of the tread, and particularly against the comparatively small surface area of the stair nosing. It is for this reason that, usually, stair erosion first appears on the nosing rather than on the tread. The result, in an extreme form, may be to form quite a dangerous ramp at the nosing. In a recent court case, it was argued that the front of a step on an old stair was so badly worn that it had in effect turned into a very steep (45-degree) ramp for the last 1½ inches (3.8 cm) of the nosing. Because the tread was quite small, the victim's foot had slipped off the edge. Not all of the other treads were worn in this way, so she had not noticed or expected this condition.

5.1.3 Composite Erosion

Where a stair has been used heavily for both ascent and descent, the tread may eventually take up the composite shape shown in figure 5.4. The precise shape of the curve will depend primarily on the dimensions of the tread and the material of the step.

5.1.4 Lateral Erosion

No matter whether the erosion is caused by ascent, descent, or a combination of the two, it may occur at any point across the width of the stair that the feet can reach. The space occupied by the feet is less than that needed for the hips and shoulders. Therefore, if the stair is hemmed in by walls and balustrades, the feet are prevented from treading near the lateral edge of the stair. Erosion starts at some distance in from the lateral edges and increases to an apogee(s) before decreasing again. Figure 5.5 illustrates erosion of this genre.

5.2 Understanding Flow from Observations

The flow of a stream of people on stairs is composed of the motions of many discrete particles, and much of pedestrian flow theory is derived from an analogy to fluid flow. Unlike liquid particles, however, pedestrians are self-directing. They can sway or even halt their own and even the whole stream's movement under certain conditions. Goffman (1971, 5, 8) talks of pedestrians as vehicular units that can twist, duck, bend, or turn sharply, and therefore, unlike motorists, can safely count on being able to extricate themselves in the last few milliseconds before impending impact.

Each person can exert a strong influence on flow, so one way to try to understand the nature of the stream of many people on stairs is to observe how these individuals respond and what influences their choices. Of course, the stream of traffic may not follow the route that any individual may take, however, each person is affected to a degree by the motion of the others. The route that a person chooses to take in climbing an empty stair may be quite different from the route options available at rush hour when the crowd has captured and partially or completely filled the whole stair and choices are limited.

Nevertheless, the crowd is aggregated from these discrete units. Its motion is affected by what is preferred, what is possible for the human body, what is tolerable, and what is culturally acceptable. And if the erosion studies are an indication, individuals respond to stairs, like other paths, in a fairly consistent way.

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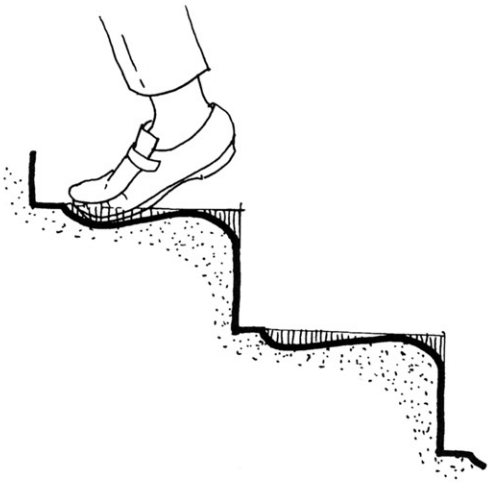
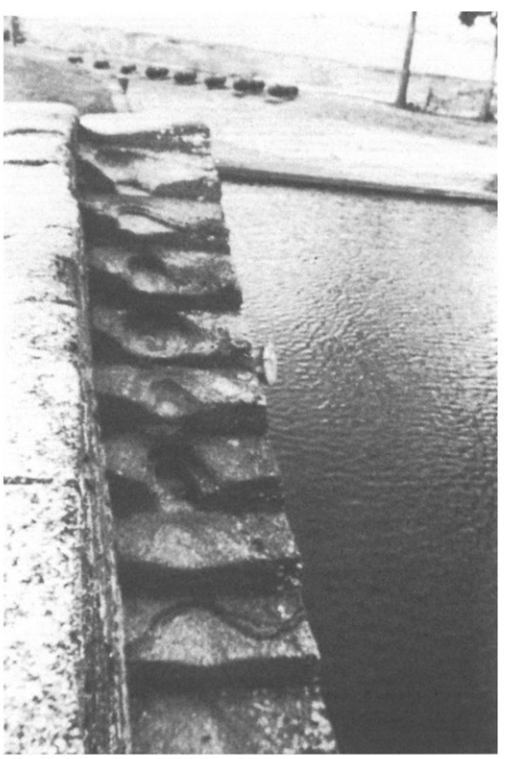


5.4 Composite erosion



5.5 Lateral erosion, stair in St. Augustine, Florida

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5.2.1 Observed Movement and Behavior

Stair erosion furnishes the physical evidence that human behavior on stairs is largely consistent over time, not random. The evidence suggests that some behavior is generalized from stair to stair, particularly where the stairs (and their environments) are similar. These deductions have been corroborated by observing people using stairs.

Observing the users rather than the use offers additional bonuses. Useful as the testimony of erosion is as an unobtrusive measure of patterns of stair use, it is inevitably limited and mute about the interpersonal and intrasocietal traits of the users. An erosion pattern may suggest a poor fit between stair and user habits, but it cannot demonstrate conflicts. Nor does erosion reveal whether there are different responses by different types of users.

Field observations can show whether the young respond to stairs differently from the aged and whether there are responses attributable to gender or race. Observations can answer questions about who uses handrails and under what circumstances.

The aim of the field observations in a 1974 study (Templer 1974) was to examine the behavioral interaction between people and stairs of various layouts, for simplicity, those complex transactions that occur when more than one person uses the stair simultaneously were excluded. Nevertheless, some general conclusions about the influence of these conditions were noted.

The observers studied the routes people selected as they traversed stairs of different configurations and vicinages. They also observed other aspects of the stair use process—handrail use, speed of ambulation, eye scanning motions, and which foot is used to take the first step. And they noted whether age, gender, and racial differences affected these actions and the choice of routes. From the evidence of erosion and from the field observations, certain behaviors are apparent.

5.2.2 Evidence of Erosion

One might expect to find evidence of all types of erosion to some extent on all stairs that are used for both ascent and descent; however, stairs exhibit erosion patterns as individual as the environment that contains them. The stair in figure 5.5 confirms the obvious: the stair is narrow and offers users a narrow range of alternative positions for the feet. Figure 5.6 shows a different pattern: this stair (in Orvieto) is wide enough so users may choose a path to follow. (One can also hypothesize that the security offered by the handrail on one side has skewed the erosion pattern to that side.)

5.3 Findings From Observing People Using Stairs of Various Layouts

5.3.1 Straight Flight Stairs

Figures 5.7 and 5.8 illustrate the paths chosen by people ascending and descending a straight flight stair in New York. In both ascent and descent, most people kept to their right on the stair; however, in descent, nearly one-fifth kept to their left. If most of the people kept right by custom, then why, during descent only, did so many use the left side? A possible explanation is that maneuvering and changing course in descent is much easier than in ascent. The user can quickly switch sides if an ascending person keeping right approaches.

Figure 5.9 shows the erosion pattern of a stair leading down to a subway station in New York. Here the erosion is of two

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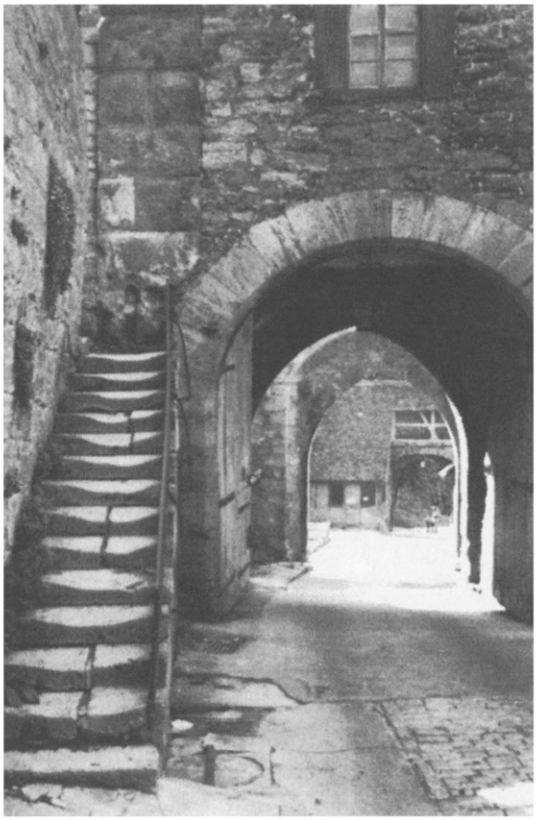

5.6 *Steps in Orvieto*

kinds. One kind is from descending traffic predominantly keeping to the right. This can be seen from the erosion at the nosing (see fig. 5.10 for detail). The other kind is from ascending traffic keeping to its right, seen (less clearly) by the erosion within the treads.

It would certainly be useful for stair and environmental design if one could conclude that the rules of the road are generally observed (at least in New York subways). Certainly on this particular stair, there is evidence of separate up and down streams by and large keeping to the right. Is this the result of cultural patterns, rush hour incentives, location of the stair in relation to other features of the station and its surroundings, the keep-right habit, right-handed people reaching for the handrail, or a combination of all these and other factors? At eight subway stations examined in the 1974 study, all of the staircases had distinct erosion patterns that showed the streams of traffic predominantly keeping to the right, regardless of the location of the stairs.

Of course, many stairs within the subway system show a variation within this pattern without contradicting the overall observation. There are stairs where the erosion of descent is marked throughout the stair width (though more extensive on the right); however, this occurs at stations where passengers must decide above ground whether they wish to ride uptown or downtown. There is no underground connection between the two platforms. The majority of the stair's users are those going downtown, particularly at the morning rush hour, so they use the stair for descent only. When returning from downtown, they ascend from the station by the

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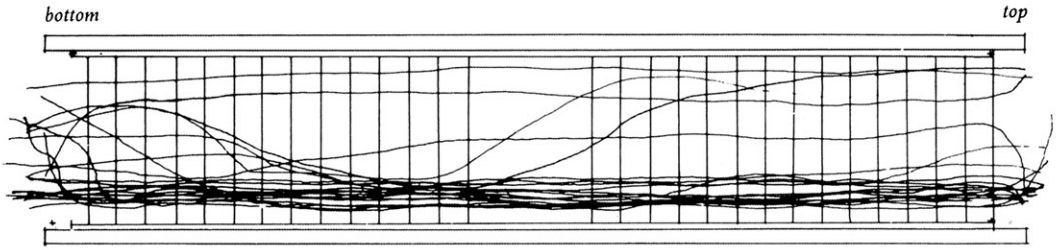
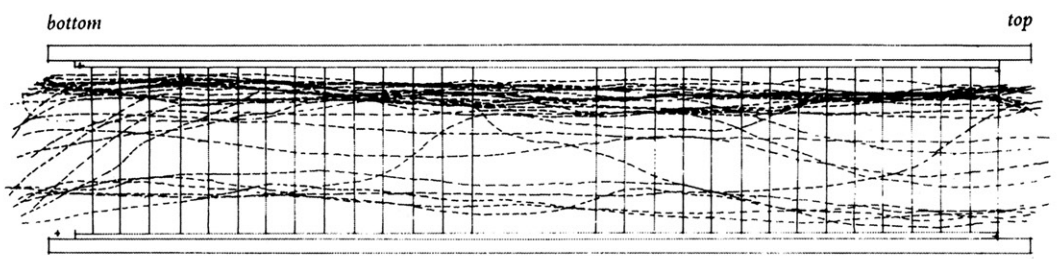


ASCENT

5.7 *Straight flight stair, ascent traces*



DESCENT

5.8 *Straight flight stair, descent traces*

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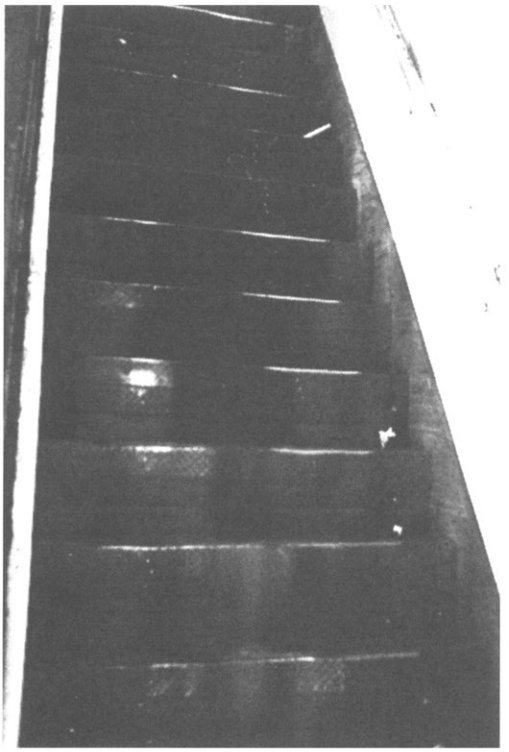
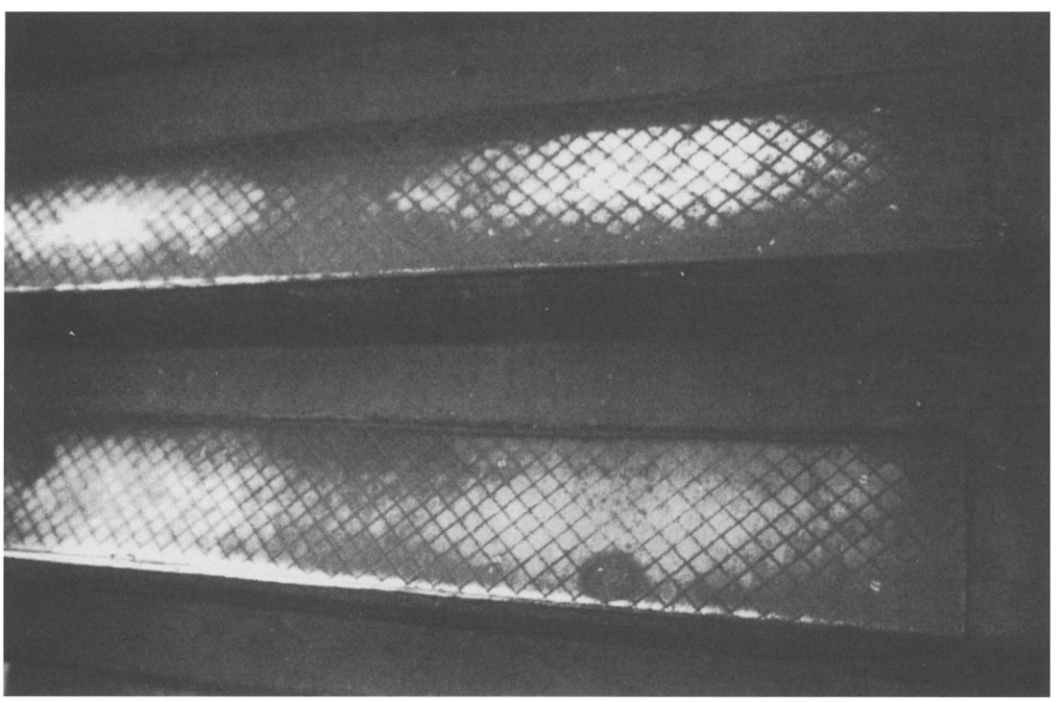


5.9 *Ascent and descent erosion*

5.10 *Detail, ascent and descent erosion*



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stairs on the other side of the street. These stairs show no significant descent erosion patterns. So at rush hour, as one might suspect, when most of the pedestrian traffic is commuting in the same direction, the whole width of the stair is used. The greater volume of traffic using the right-hand side as evidenced by the stair erosion (and handrail erosion) probably reflects a reversion to the keep-right rule after the morning rush hour.

Where a stair is divided into two by a center handrail, the keep-right rule is usually extended to include the whole right-hand portion of the stair.

5.3.2 Directed Straight Flight (Zigzag) Stairs

A stair on which access and exit directions to certain flights are controlled by the layout makes an interesting contrast. The

Grand Stair leading down into the main concourse at Grand Central Station in New York (fig. 5.11) has a matched pair of stairs, each consisting of three flights, each stair the mirror image of the other. In effect, this provides six straight flights coupled by landings.

At one end of each flight, pedestrians must take a 90-degree change of direction, followed by a 90-degree turn in the other direction at the end of the next flight. These six flights offer a singular opportunity to observe the effect of various entry and exit directions in a way that was not possible at the straight flight Port Authority stairs. Furthermore, all the flights are at one site and used by pedestrians equally and are therefore strictly comparable. These are the conclusions derived from the observations:

1. People perceived the two stairs as alternative routes.

2. In certain instances, significant associations were found between exit or entry directions and the routes taken on stairs in ascent and descent. In general, this was found to indicate consistent behavior. There was no evidence that the approach direction controlled the route chosen.

3. In ascent and descent, people chose the right channel predominantly, unless this required them to travel significantly farther than the most direct route.

4. In ascent, having chosen the right channel, users showed no inclination to stay to their right (except on the left flight), but users of the left channel predominantly stayed to their right. In descent, people chose to keep to the right predominantly no matter which channel they took.

5. On landings, taking the shortest route was customary.

6. Some users took the shortest route on the stairs, but the majority did not take shortcuts (except at the top or bottom). To do so would cause them to violate the keep-right custom. However, the greater the advantage offered by the shortcut, the larger the number of people who took it.

In assessing these two stairs, it is useful to examine the congruence between user and stair as indicated by the probability of conflicts. The potential for conflict arises where substantial numbers of ascending and descending stair users compete for the same territory. The conflicts do not usually produce physical contacts but require rapid evasive action to avoid contact. A confused pattern of use may ensue that reduces the stair's capacity and congruence in terms of uneventful and comfortable flow.

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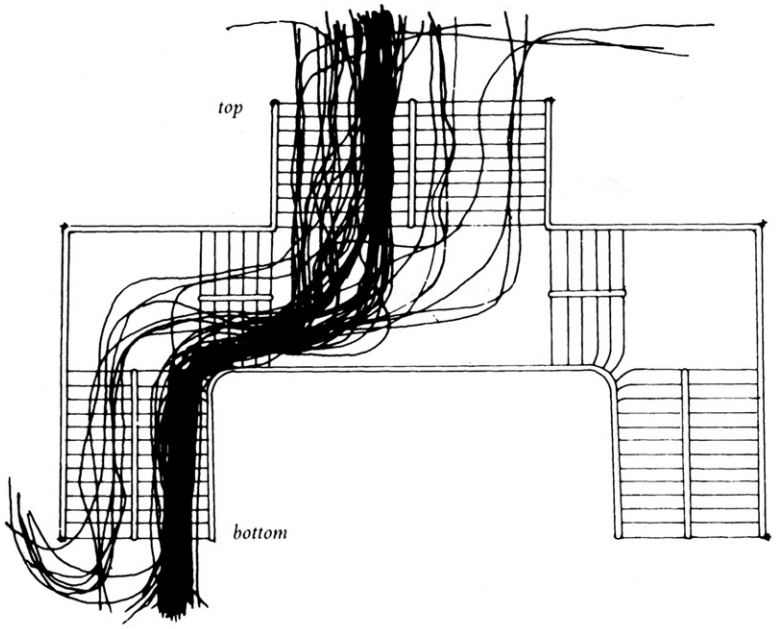
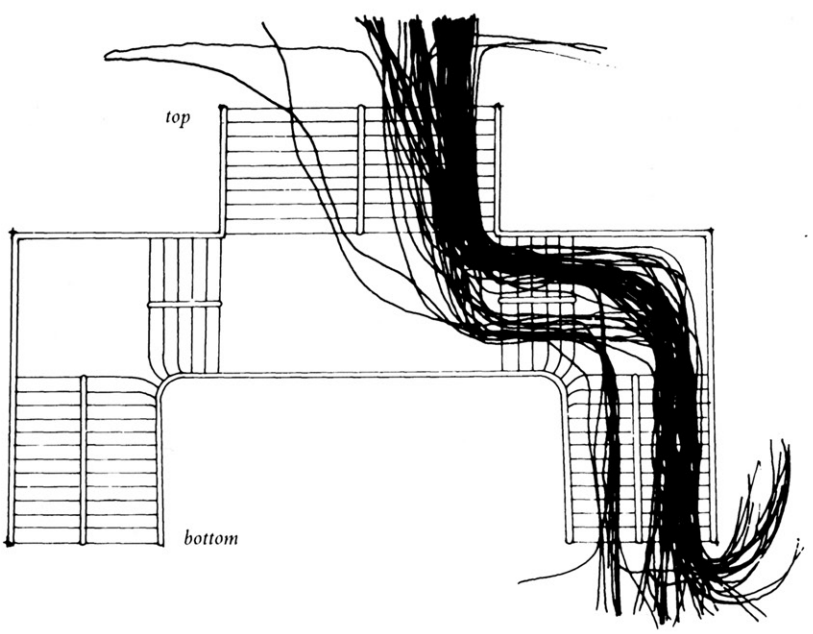


Left flight *Right flight*

ASCENT



Left flight *Right flight*

ASCENT

5.11 *Ascent and descent patterns, Grand Stair at Grand Central Station* *(continued on next page)*

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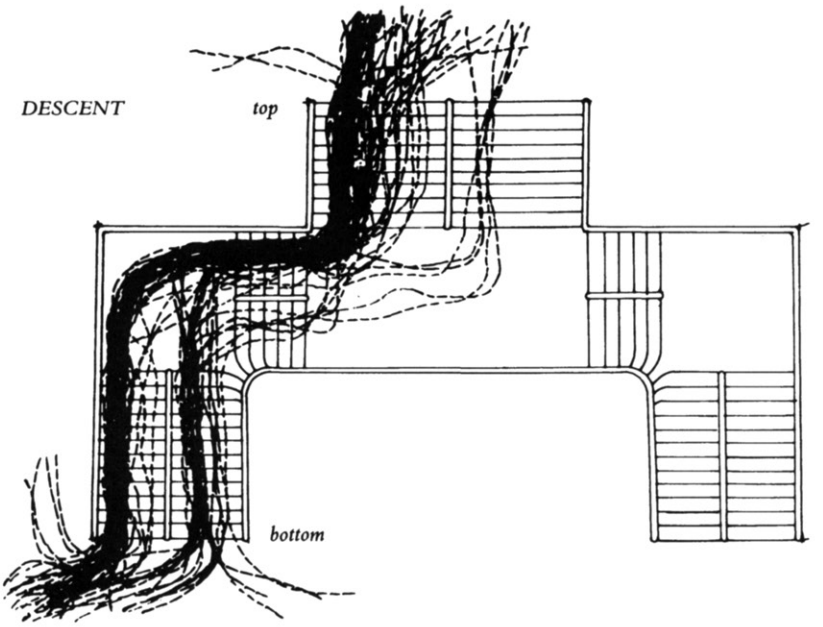

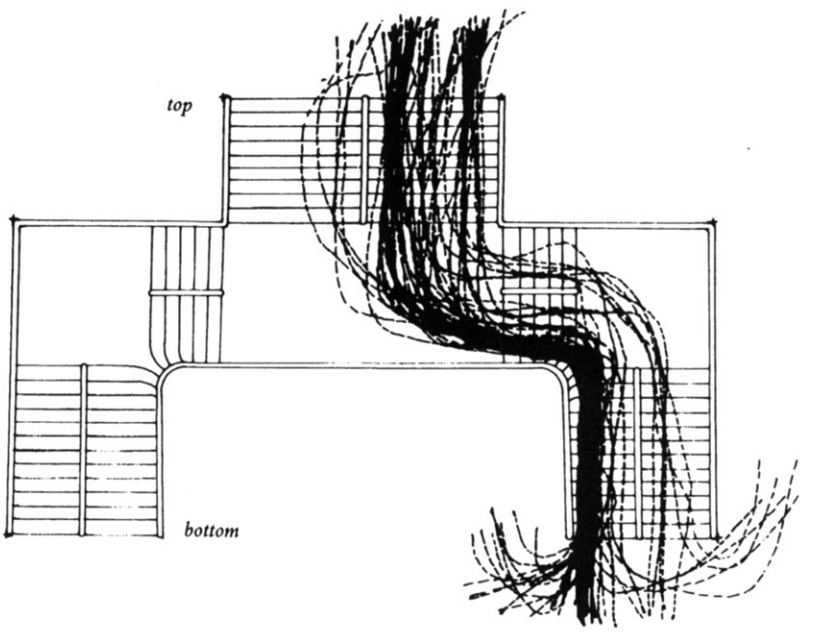

DESCENT

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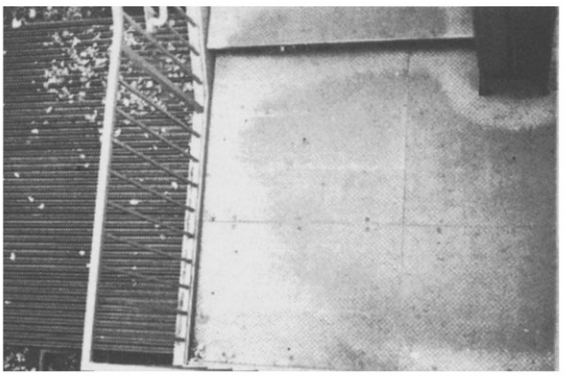
Coupling together the ascent and descent patterns of these two stairs, the conventionally channelized middle and bottom flights show less potential for conflict than the curiously channelized top flight. Second, the zigzag layout of the routes increases the potential for conflict because it encourages people to switch channels to take the shortest route. The landings and the top flight are the most likely places for conflicts to occur. The right flight is marginally more congruent than the left flight. The movement patterns are more consistent and less dispersed.

Conflicts on this stair are most likely to occur on the landing, particularly because the approaches are hidden. The left channel of the top flight also manifests a confused pattern because some of the ascending traffic takes this as the shorter route.



5.12 Landing of a dogleg stair

5.3.3 Dogleg Stairs

Dogleg stairs generate their own distinctive erosion patterns. Figure 5.12 shows half of a landing of a steel dextral dogleg stair (that is, a dogleg on which ascending traffic turns to the right at landings). The erosion pattern shows how the stream of traffic flows around the newel at the center of the landing, ignoring the corners. From the keep-right rule, one would expect to find ascent erosion predominating on the inside of the stair—and this is the case. Descent erosion, on the other hand, is not so clearly confined to the one area of the treads. It becomes increasingly diffused as the landing is approached. When there is no ascending traffic (keeping to its right on the inside of the stair), the descending stair users tend to move to their left to avoid having to take the long way around the landing. If one must seek an explanation for this shortcutting behavior, part of the answer must lie in the urge to conserve energy, for just as people automatically, without conscious thought, select a walking speed of around 3 mph (4.8 kmph), so they seek to conserve energy by avoiding unnecessary movement. In another context, Alexander (1967) calls this the principle of least action.

A sinistral dogleg (where one descends making right turns) leads to a different pattern of erosion (and movement). Here, the inside route, when keeping right, belongs to the descending traffic. This time the ascending traffic is on the outside and is even more inclined to move to the left as the landing is approached. Presumably this occurs because ascending stairs escalate the metabolic rate greatly compared to normal walking or descending. The drive to conserve energy by taking shortcuts is then naturally amplified. Therefore, in the sinistral dogleg, descent erosion occurs on the inside, close to the landings particularly, ascent erosion moves toward the inside also.

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Figure 5.13 illustrates the movement traces observed on a sinistral dogleg stair. For this stair, it was concluded that

1. In ascent and descent, most people choose to use the right channel.

2. Taking a shortcut at the landing is standard behavior.

3. Many people ascending the stairs switch to the left channel at the landing to take the shortest route.

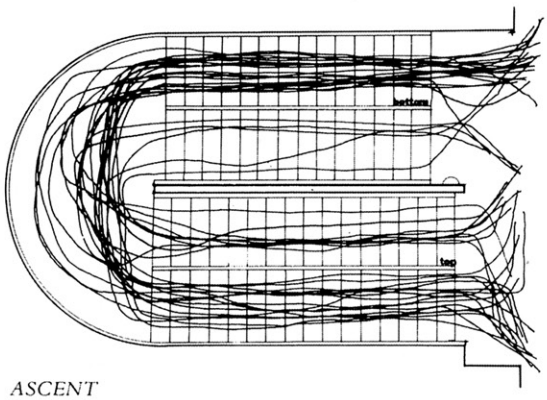
4. No significant association between routes used, shortcuts, and exit and entry directions was observed.

5. People who use the left channels predominantly keep to the right. This is not the case of those who use the right channels.

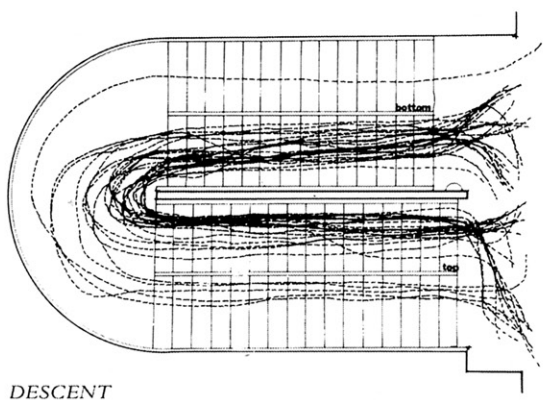
As a result of the conclusions drawn from the observations on this stair, it was decided to see whether there are differences in movement on sinistral and on dextral dogleg stairs. Does a dogleg stair that ascends clockwise (dextral) reduce conflicts by giving the ascending traffic the shortest route? This idea can be tested by observing a matched pair of dogleg stairs that spirals upward in opposite directions.

Such a pair ascend up into the main concourse of Grand Central Station in New York, below the zigzag stairs already described. Each stair consists of three flights without channels, coupled by landings. Having three flights each, these stairs are not strictly true dogleg stairs; however, *dogleg* is the most appropriate appellation.

Figure 5.14 illustrates the paths chosen by people ascending and descending each flight. There is an association in the bottom flights of the two stairs between entry directions and routes chosen on the right



ASCENT



DESCENT

5.13 *Dogleg stair traces, ascent (continuous lines) and descent (dotted lines, in right figure only)*

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stair. The top flight is curiously constructed in that not all of the stair is easily accessible; it is masked by a dividing wall. Understandably, few stair users took the route that runs next to this wall.

The following conclusions were drawn from the studies:

1. In some instances, there are significant associations between entry or exit directions and the routes chosen. These associations, however, indicate consistent behavior rather than that the users' paths were influenced by these directional movements.

2. The stairs are wide and not channelized. Where it is easy to keep right—on the left stair in descent and on the right stair in ascent—the users generally follow the custom. However, when keeping right requires the users to take a much longer route, many people move over to take a shorter (but not always the shortest) route.

3. Taking the shortest route at landings is standard behavior.

4. The curious layout of the top flight provides little assistance to the stair users, and this is reflected in the dispersed pattern of movement.

The top flight, by its layout, creates conditions where conflicts are likely to occur. Conflicts are likely to occur at the landings also and on the middle flights, which are wide and without channels. The most convenient way of using these stairs is to use the right stair for ascent and the left stair for descent. Alternatively, channelizing might make the stair width more comprehensible and acceptable to users.

If we compare sinistral dogleg stairs to dextral dogleg stairs, then the dextral stair is more congruent with the habitual movement patterns as indicated by the paths pedestrians take. Ascending to the right and keeping right is easier and less likely to encourage shortcuts than ascending to the left, which is the longest route. Of course, in descent the reverse is true, but descent requires much less effort. In descent, also, the user is able to change directions and respond to traffic conditions more easily and quickly. The user can even take the shortest route and switch if ascending traffic keeping to its right is encountered. The right dogleg stair is dextral and its traffic pattern is more consistent than that of the left stair, particularly in ascent, despite its width and lack of channelization.

From these dogleg stair examples, the natural inclination to take shortcuts is shown to modify any impetus to keep to the right. Other factors, of course, affect the extent and probability of the shortcut—the width of the stair and the environment served, for example. Figure 5.15 shows an instance of the former, a streetwide urban stair in Morocco. A distinct path cuts obliquely across the stair (from the left background to the right of the donkey).

Where shortcuts are generated by the local environment served, the erosion pattern can often be seen at the head and foot of stairs. Typically this behavior results from the location of the stair in relation to certain environmental conditions. For example, where the approach to the stair lies at right angles to it, then people tend to enter or leave the stair at the closest point to their next direction of travel. They approach the top of the stair from the left, at right angles to the direction of the flight. They take a shortcut around the top corner before moving to the right to descend. Finally, to exit in the next direction of

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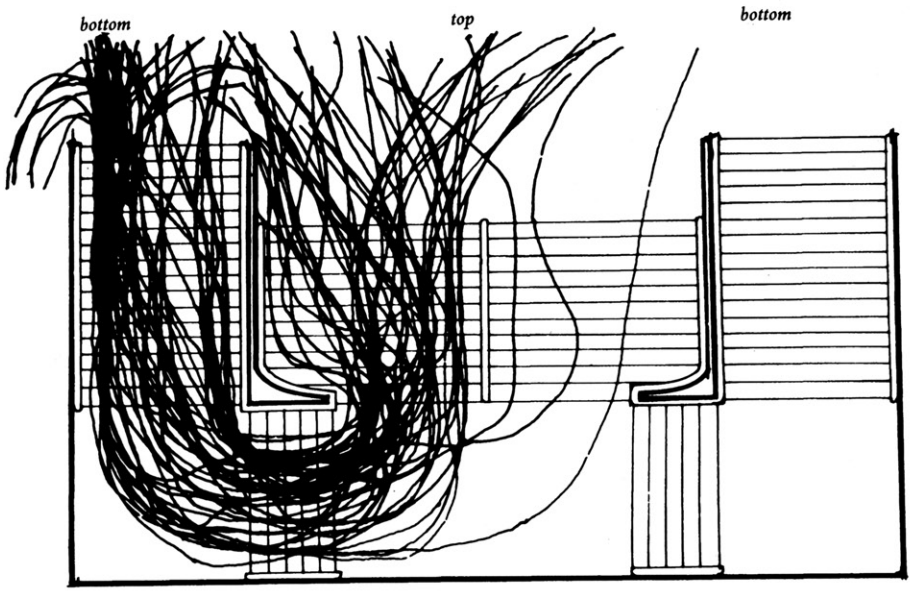

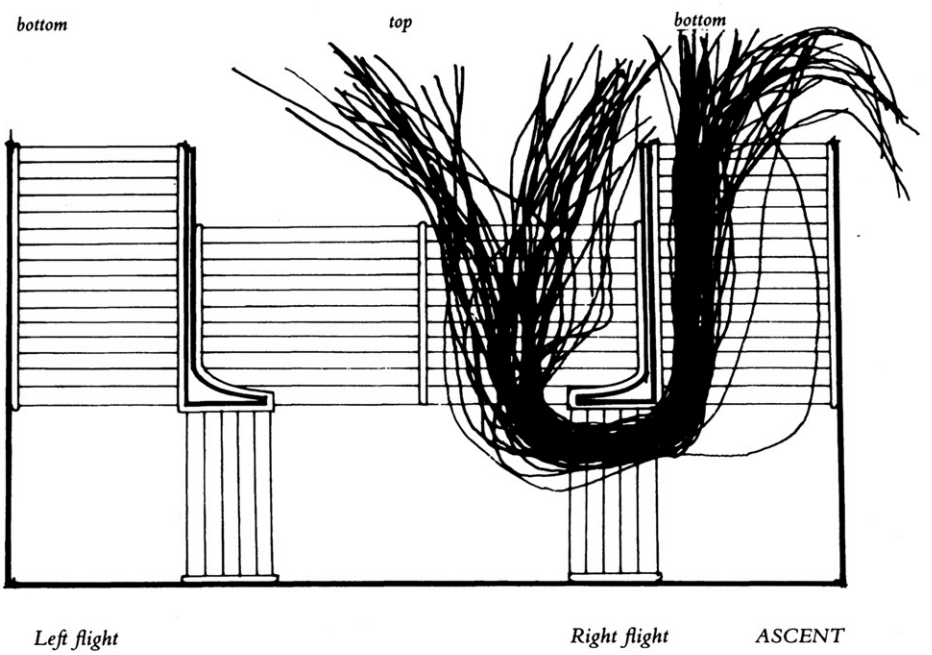

Behavior on Stairs

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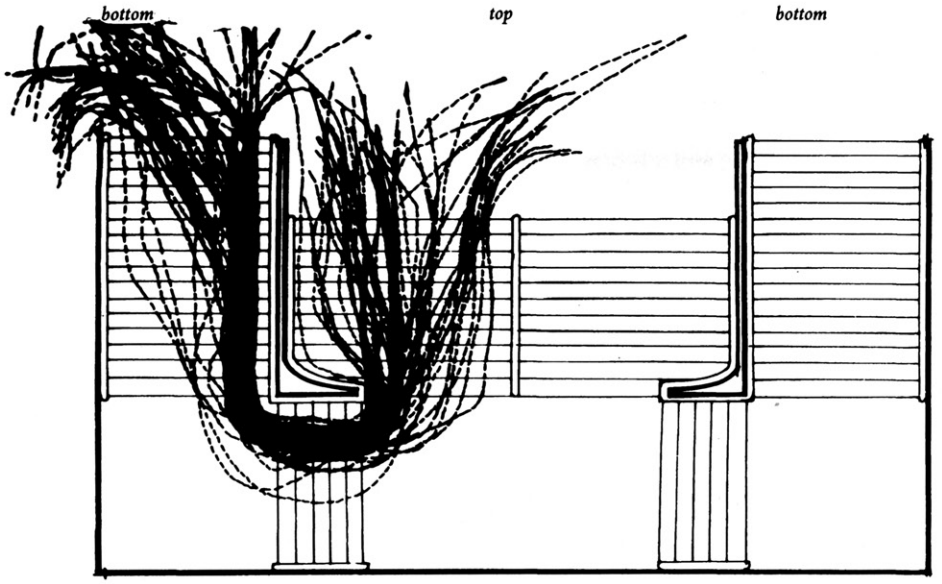

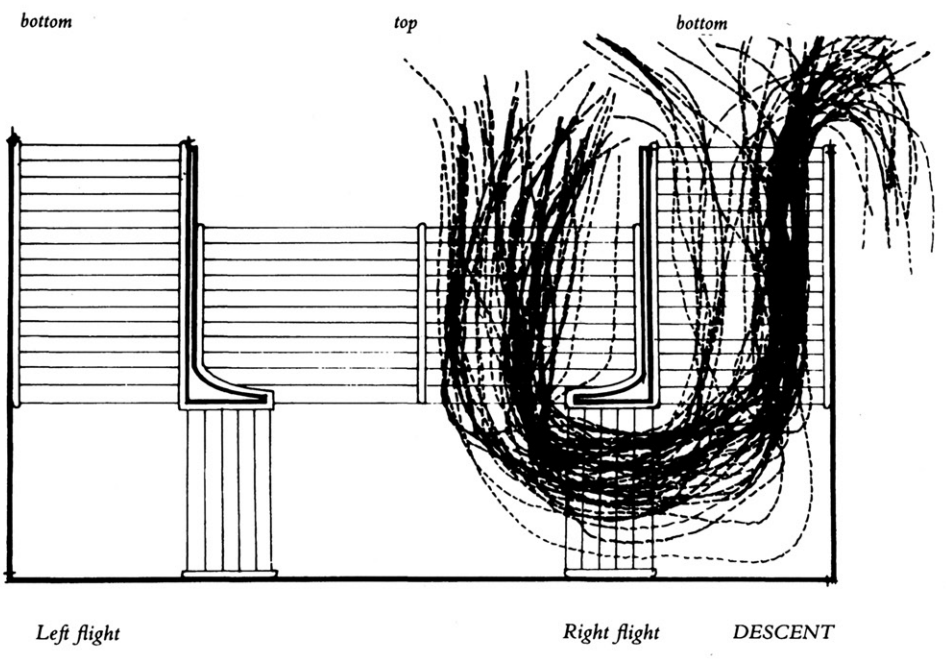

5.14 *Pair of dogleg stairs, ascent and descent traces*

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5.15 *Street stair, Morocco*

travel—to the left, at right angles again—they cut across to the left of the stairs as they approach the bottom. Ascending traffic has the "right" to the shortest route and does not need to take any shortcut.

5.3.4 Helical Stairs

The relationship between dextral and sinistral layouts and the paths pedestrians take is most clearly shown on helical stairs. Many of the patterns of erosion that occur in the dogleg hold true for stairs formed of combinations of straight flights connected by landings. However, stairs with treads that vary in size—in circular and elliptical helical stairs, for example—introduce a further factor to influence behavior.

In the typical helical stair, the tread increases from a minimum dimension at the well or newel up to a maximum at the outer periphery. Figure 5.16 illustrates a stair of this type at Cambridge, England. Most of the erosion (composite) predominates in one area. This stair is not so narrow as to offer no alternatives. One can deduce that because it is a helical stair with variable tread dimension, the pedestrians choose the most comfortable tread size consistent with the fixed riser dimensions. However, this might be quite wrong, for as Webb et al. (1970, 44) have pointed out, "An important bias is that each footfall is not necessarily an independent event. Once a groove on a stair becomes visible, for example, those who walk on that stair are more likely to conform to the position of the groove than are those who walked before it became visible. This is partly due to the physical condition of the stair, which tends to slide the person's foot into the

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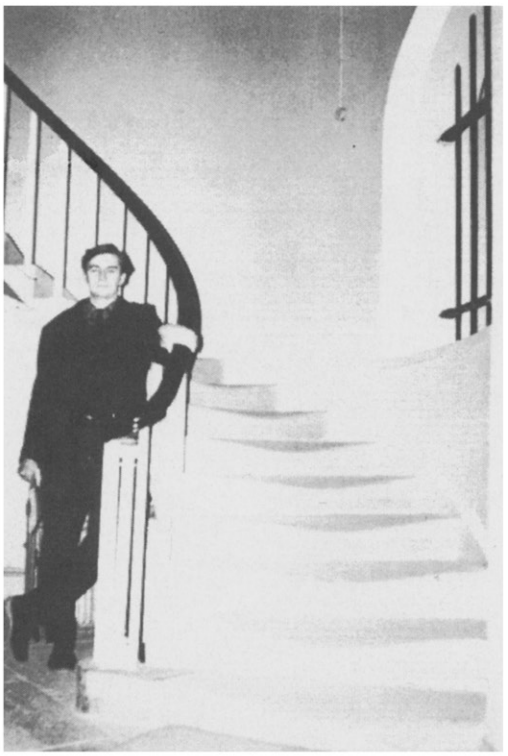
groove, and also possibly due to a response tendency to follow in the footsteps of others." Nevertheless, for the groove to become visible, a pattern of behavior must have occurred. On this stair, there is a handrail on the one side only, the inside. Perhaps this draws the traffic flow closer to it.

The helical stair is a special example of the shortcut phenomenon because the inner perimeter is so obviously shorter than the outer. It will therefore offer a continual advantage—and not just at the landings. In the stair shown in figure 5.16, there is no evidence that New York's apparent keep-right rule extends to Cambridge, England. (In England, one might expect the traffic to keep left, for vehicular traffic, which may be the example for the rule, travels on the left.) Also, there is no evidence that ascending or descending traffic adheres to specific and separate routes. The stair is probably too narrow a spiral stair for this to occur. Probably people choose the route closest to the inside to make use of the handrail and the shortest route. Then they move outward to select a reasonable, comfortable, and safe tread size to walk on.

A matching pair of helical stairs ascends from the entrance hall of the New York City Hall up to the rotunda. As they ascend in opposite directions, they offer an excellent opportunity to examine the usage patterns generated by the alternatives. Figure 5.17 shows the paths taken by people ascending and descending each flight. There is no handrail on the outside of the stairs. It is hard to see how this could explain the dispersed pattern of the right flight. However, the handrail on the left may have increased the volume of those that kept left.



5.16 *Helical stair, Cambridge, England*

The following conclusions can be drawn about helical stairs:

1. Stair users predominantly keep to their right in ascent and descent only when this is the shortest route.

2. Ascending the left flight, and descending the right flight is not a simple matter of choosing a route. This is clearly demonstrated by the dispersed patterns.

3. Exit and entry directions do not appear to be influential in route choice.

4. Exit and entry directions encourage people to take shortcuts at the top and bottom of the flights.

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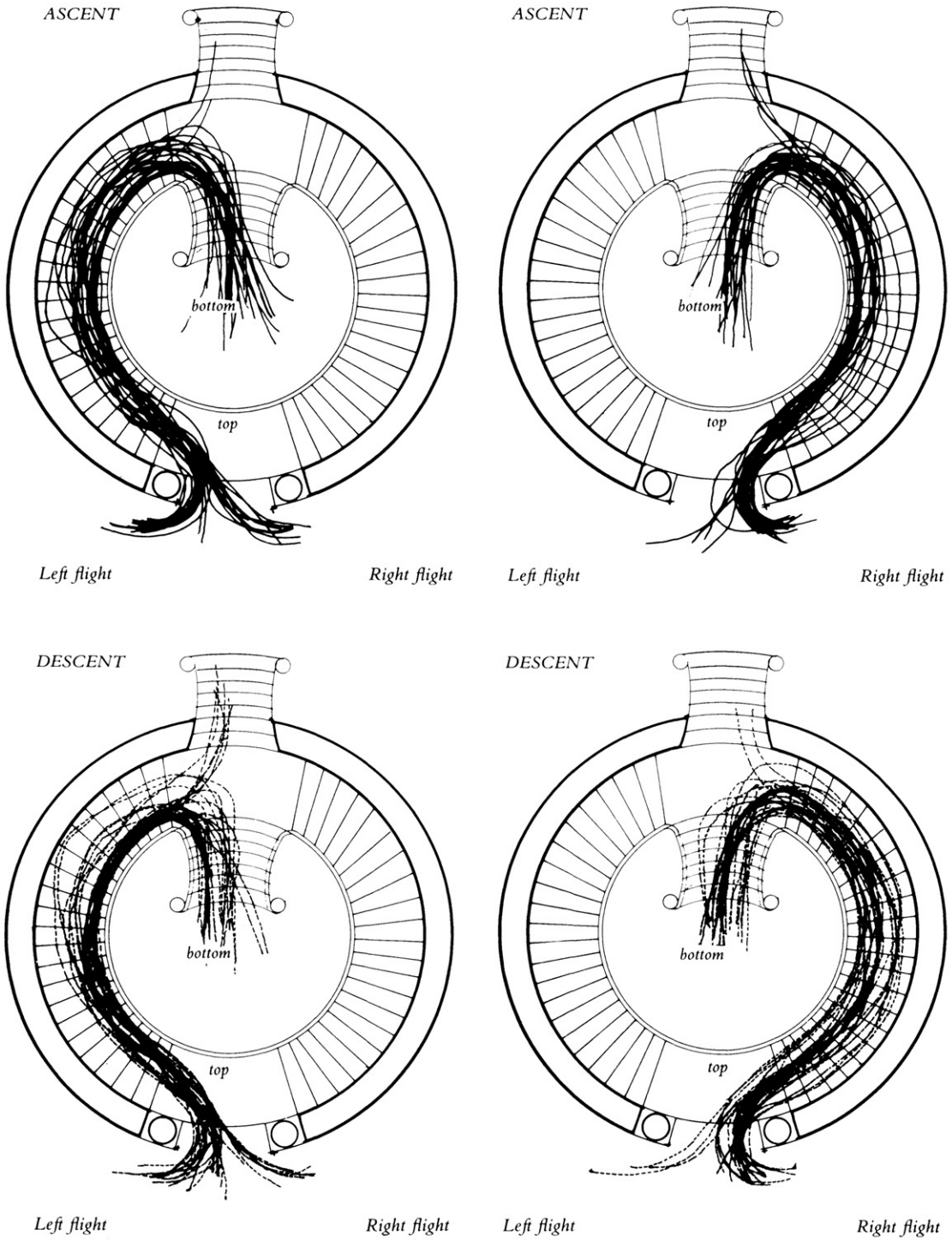

5.17 *Helical stair traces, ascent* (top) *and descent* (bottom)

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Both flights are inherently more likely to produce conflicts than the other types of stairs. The outside route is patently longer than the inside, and users will keep to their right only if it is not manifestly longer. Conflicts are likely to occur on the flights as well as the landing.

The right flight is a degree more congruent with user needs than the left flight. During the effort of ascent, the pedestrian can legitimately take the shortest route. On the left stair, descent is easier and the route more congruent with user habits. However, ascending the left stair is less convenient. If one takes the short route, one must keep left against the traffic stream. From the patterns, people are reluctant to do this and exhibit their uncertainty and hesitancy in the dispersed pattern.

5.3.5 Summary

Examples of straight flight, dogleg, and spiral staircases show that each layout engenders its own particular movement pattern—in addition to the obvious directional thrust for which the stair was designed. Besides the general route direction imposed by each type of stair layout, the routes are determined by two major factors. First, people (in New York at least) habitually keep to the right of the stair when ascending and descending. Second, people do not habitually take the shortest route when traversing stairs because this would conflict with the keep-right pattern. However, they habitually take shortcuts at certain key areas: across landings and at the entrance and exit of the stair. Within the constraints of the keep-right situation, taking the shortest comfortable route is a universal and predictable stair use habit, not limited to New York. It originates from the natural desire to conserve energy (and perhaps the unnatural desire to save time). The shortcut is generated by the stair layout and its interface with its environment at the top and bottom.

5.4 Movement Patterns of Groups of People Using Stairs

No methodical and quantified observations of stair use by several people simultaneously have been carried out (except in terms of capacity, as discussed in the last chapter). However, as an exploratory exercise, people exiting from a subway station in New York were recorded as they descended into a connecting walkway. The stair is a straight flight stair with two channels. It is close to the platform and approached from directly behind but somewhat to the left.

People often approach the stair in platoons as each train discharges its passengers. Because the users approach at different speeds, the platoon builds up to form a wedge and then dies away again. The first arrivals, descending the stair, took the right channel but did not usually keep to their right. As more people arrived, the right channel gradually filled. People usually "capture" the stair in files from the right. After the right of the channel is filled, the second file from the right is occupied, and so on. If, however, a group of two or more arrive at the stair simultaneously, all directional codes are set aside, and they occupy as much of the stair as they need.

After the right channel is fairly full, the platoon spreads into the left channel, again filling it from the right. If a pedestrian is balked by a slower-moving person or any holdup in the stream of movement, the re-

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action is to switch immediately to the nearest open route, even if this means moving over to the left. Then, overtaking to the left is the usual mode. However, people ascending demand and are customarily given the right of way if they are keeping to their right. As the platoon diminishes, people gradually revert to the keep-right custom again, although on the right channel they are less likely to keep right than on the left channel.

These observations show that the movement patterns of people in groups and platoons follow many of the habits manifested by individuals. However, as stair density increases, pedestrians progressively take over as much of the stair as they need, so long as this does not interfere with the rights of people moving in the other direction.

A special aspect of behavior on stairs is where crowds surge onto a stair in an uncontrolled and desperate manner, resulting in chaotic movements and even loss of life. Fruin (1985, 110–113) says there are four interacting components to this sort of crowd behavior, all of which are always present: time, space, information, and energy.

Crowd disasters occur in the short space of time after the capacity of a pedestrian facility has been exceeded. This is usually caused by the crowd's perception of urgency—to escape from a danger, for example, or even to get into an entertainment event. The disaster occurs because the critical density of the facility (the stair, say) is limited by the space available. At this time, individual movement is superseded by the shock waves propagated through a mass of people. Because the individuals in the crowd have no information about what is happening up ahead and because they are infected with the mood of the crowd (urgency, high spirits, and so on), they continue to press forward. Then the energy generated by a crowd out of control is enough to carry people forward, crushing some and even trampling others. Stair capacity and layout to minimize the effects of this sort of behavior must be considered.

5.5 Behavioral Reactions to Stairs and Their Surroundings

In addition to the studies of the flow of people on various types of stair, researchers have interested themselves in other aspects of stair use. Are there consistent patterns of handrail use? (This is discussed in the next chapter.) Do people start their ascent or descent with the left or right foot? Is there a consistent pattern of eye movements as people use stairs? How fast do people walk on stairs?

5.5.1 Foot Used to Take the First Step

On some flights, in ascent or descent, people are more likely to use a particular foot to take the first step. Sometimes the left foot predominates, and sometimes the right. The pattern is not generalized from stair to stair. Observational data suggest that, although the right foot may be used more frequently than the left in ascent and descent, this difference is not statistically significant. There is no significant association between the foot first used and the age, gender, or race of the subjects in ascent or descent.

5.5.2 Speed of Ascent and Descent

With increasing age, the time taken on a stair also increases (but gender and race are not influential factors in speed of traverse on stairs). Very few studies of riser-tread combinations and speed of ascent have

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been reported in the literature. On the basis of these studies and using least-squares criteria, the multiple linear regression prediction equation that fits the available data best is as follows:

$$V_s = 76.98 + 2.106R - 2.543\ T$$

where V_s = rate of vertical ascent in feet per minute
R = riser height in inches
T = tread depth in inches,

or in metric units

$$V_s = 23.47 + 0.253R - 0.305T$$

where V_s = rate of vertical ascent in meters per minute
R = riser height in centimeters
T = tread depth in centimeters.

The equation for the rate of horizontal travel (H_s) in feet per minute (with T and R expressed in inches) is therefore

$$H_s = \frac{T}{R}(76.98 + 2.106R - 2.543T)$$

and in meters per minute (with T and R expressed in centimeters)

$$H_s = \frac{T}{R}(23.47 + 0.253R - 0.305T).$$

It is interesting to compare this equation with that given by Fruin (1970, 14) for walking on the level,

$$H_s = \frac{(T - 1.188)60}{0.257}$$

where T = length of pace in feet
H_s = walking speed in feet per minute.

At a normal level walking speed of 270 feet per minute (82.3 m/min), this formula produces a pacing distance of 2.35 feet, which is slightly more than 28 inches (0.72 m). (This is an average; pacing length varies with age, sex, physique, and physical condition.) Using these values of $T = 28$ and $H_s = 270$ in the formula for horizontal travel on stairs, a value for $R = 0.77$ inches (1.95 cm) is obtained that is very small, as it would be in level walking. This suggests that the equations are of the correct order of magnitude.

5.6 Stair Use as a Behavioral Process: A Conceptualization

Stair use may be hazardous, but so may driving a car or crossing a road. The danger may be apparent—a torn carpet, narrow treads, low light—or it may be unrecognized—a broken tread or ice on the step. How do we behave in the face of the dangers presented by stairs? Hale and Glendon (1987, 40) have suggested a model in which our ability to operate successfully in a dangerous situation is dependent on three levels of abstraction of behavior (fig. 5.18).

At the skill-based level, incoming information engenders an automatic response. We encounter a stair and descend it without much thought; we know how to use stairs. If the stair has other people on it, our behavior changes to a rule-based level. It is not acceptable to bump into other people, so we move over to the right usually. If there are no rules or we cannot use them (somebody is ascending rapidly on our right), then a knowledge-based level leads us to cogitate (briefly) about the solution: wait for a gap, try to squeeze past, hold our ground on the right.

The Hale and Glendon model was developed for occupational safety as a way of understanding danger in routine tasks, for hazard detection, for danger labeling and assessment, and for the development of safer behavior and designs. It is a system model that forms a matrix. The y axis of

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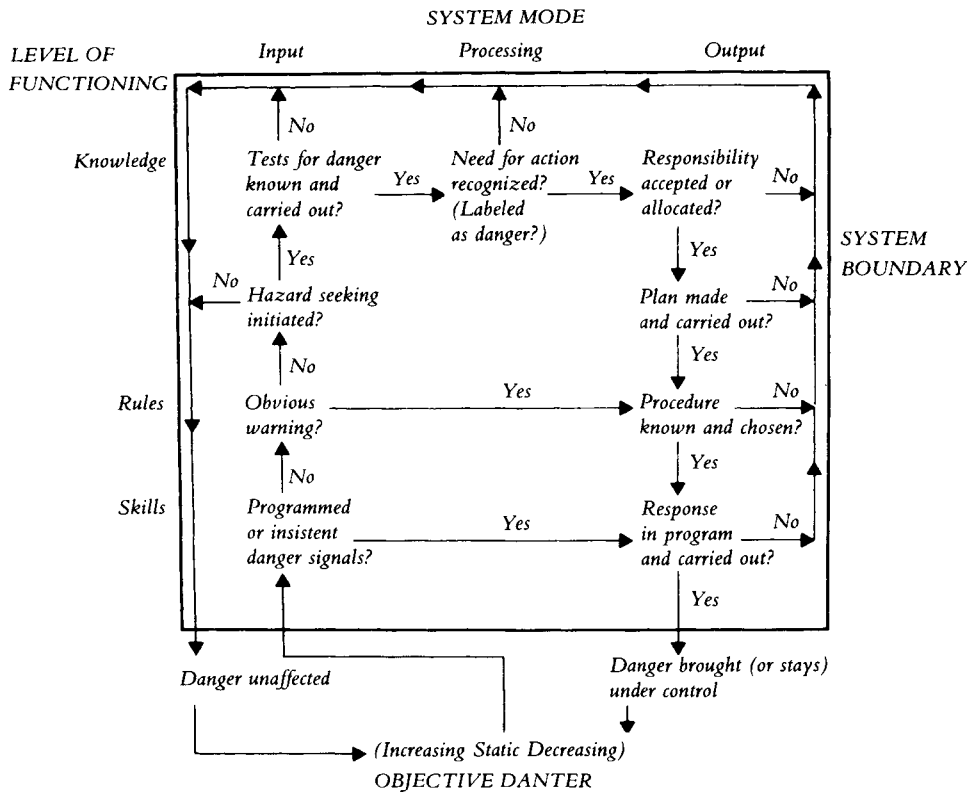

the matrix consists of the knowledge-, rules-, and skills-based levels of functioning of people. The *x* axis sets out the classic system modes: input, processing, and output. The model uses these cells as nodes at which decisions about a danger are made at the levels of functioning within the system. For stairs, the Hale and Glendon model can be amplified by analyzing stair perception and behavior by process (fig. 5.19).

The use of a stair by one representative individual in a stream of pedestrians consists of several actions, some that take place sequentially and some concurrently. Some of the actions entail deliberate decision making that affects how the stair is used. Figure 5.19 shows a conceptualization of the sequence of typical events that, for normal perception and action, must take place as a stair is approached and traversed. The process can be summed up as follows:

- Expectation (about the stair and the environment)
- Perception (through scans of the environment)
- Detection (of information, hazards, or obstacles)
- Cognition (understanding what has been perceived)
- Selection (of a route and behavior)
- Action (ascending or descending)
- Reaction (to any missteps, hazards, or obstacles)

Before the ascent or descent starts, events 1–5 (in fig. 5.19) must each occur at least once. These and the other events may occur several times during stair use.

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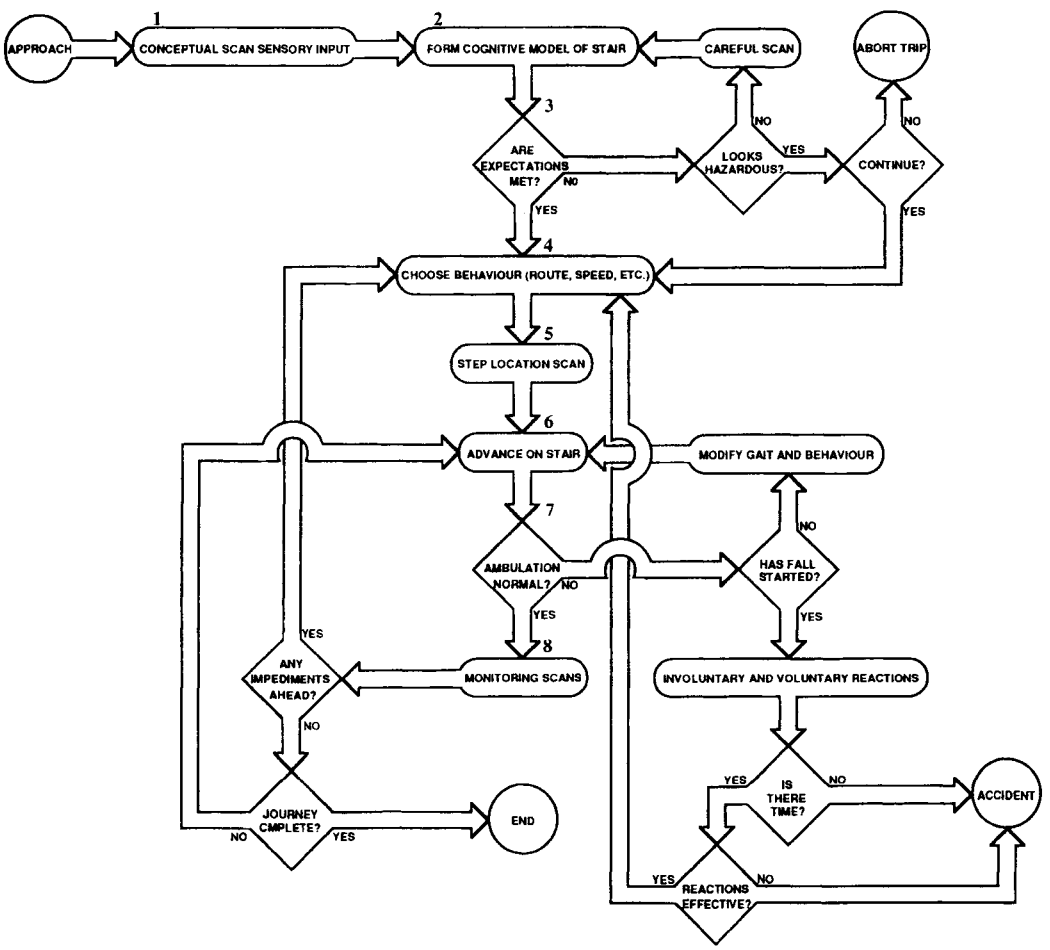
5.18 *Hale and Glendon's model for behavior in the face of danger, reprinted from Hale and Glendon (1987), 40*

5.19 *The stair behavior model*



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5.6.1 The Conceptual Scan

In the conceptual scan (or cognitive mapping) phase, event 1, we scan and sample the parts of the visual array in succession (Gibson 1966, 250), noting (to the best of our available perceptual skills) fixed and variable factors. The fixed environmental components include the stair's disposition in space and its vicinage, approach and exit directional options, its shape and apparent riser-tread configuration, obvious obstructions or potential hazards, perhaps the handrail location, and a host of minor details.

Beside these fixed factors, effective scans (for a normal, healthy person with all faculties operative) will encompass available information on the ambient conditions. Is the stair wet or slippery? How much light is available? Is there litter in the way? And, finally, what motion is taking place? For the last, the scan provides information on whether people are ascending or descending, at what speeds, taking what routes, their numbers, sizes, and ages, their behavior, whether they have affective characteristics, and whether they are carrying children or parcels, opening umbrellas, or simply hesitating.

Much of the information harvested in the conceptual scans is not immediately significant, but the human information system is skillful at layering impressions according to their current importance. Details of the environment may be seen but relegated to a level below consciousness, or selectively kept in the forefront of concern. For example, many directional signs are displayed in the subway system, and a stranger is likely to exaggerate their role in the visual field. To a native, on the other hand, the signs would no longer be consciously apparent unless they were repainted or otherwise given some new significance. This is the same mechanism that selectively tunes out unwanted background noise and tunes in a particular conversation. The products of the conceptual scan enable a cognitive model of the stair to be formed (event 2).

5.6.2 Expectation and the Cognitive Model

During the conceptual scan and the subsequent step location and monitoring scans, the area is surveyed visually with appropriate thoroughness related to one's expectations. Expectations are compared to the newly formed cognitive model. If the two do not appear to match in some way, then one is likely to abort the whole trip if the stair looks dangerous or at least to scrutinize the stair with much greater care than usual. For example, one would examine an obviously rotten or icy stair with much greater care than a stair inside a heavily used public building. We trust stairs within buildings unless there are some clues to the contrary. On a wilderness trail, on the other hand, we know that the ground may be uneven, rocky or soft, with tree roots to trip on, and so on, so we scan the path with much greater care than we will the corridor in an office building.

Any violation of our expectations may turn out to be hazardous. For example, in a recent court case, the jury was told about a young man who stepped down onto what looked like a floor. (Langley v. Combine of Fairfield Inc. d/b/a Jardine's, and Mianus River Associates. U.S. District Court, Southern District of New York, 85 Civ. 5069.) It was in fact made of insulation board and could not support his weight. He fell through the boards about 13 feet (4 m) to the floor below and was

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seriously injured. The defendants claimed that he was careless and had not looked carefully enough. The plaintiff's expert argued that there were no obvious visual clues to inform the plaintiff that the floor was not structurally capable of carrying his weight. His expectation was that it was a floor. If anything had raised his suspicions, then he, as a reasonable person, would have taken a closer look at the floor and perhaps tested its ability to carry a load. The floor failed to match his reasonable expectations.

It is often a failure of expectations that causes falls on stairs with dimensional irregularities. The scans fail to detect the dimensional differences. One expects a stair to be well built, and even quite large dimensional errors may go undetected. Falls on rather steep ramps may well be caused by the same mechanism. Pedestrians tend to trust the constructed environment. If a ramp has been provided, even if it appears to be steep, people will use it on the assumption that because it has been constructed and is not patently hazardous, it is probably safe.

Expectation should not be confused with memory. If, for example, someone has ascended a step onto a platform in a shop, it would be wrong to assume that the customer will carry this memory while examining clothes displayed on the platform. Little of our experience is committed to memory for any length of time. The visual sensory memory, or iconic memory as it is sometimes called, usually lasts no more than ¼ to ½ second in young adults (Walsh and Thompson 1978, 383–387). It is not only the visual memory that is operational; all the senses play a part. For those with severe visual impairments, the auditory-sensory store, or echoic memory, may be even more significant than the visual memory. We would do better, therefore, to refer to modality-specific sensory memories. Some sensory memories may be moved into short-term or working memory where information processing occurs. However, short-term memory capacity is not great; it can process or retain only a small quantity of information at a time. Also, if the information is not rehearsed because it is significant for some reason, then it will be displaced rapidly by other incoming information. This information may come from the sensory stores or by retrieval from long-term memory (Smith and Fullerton, 1981, 139–155). As the attention of the shoppers, in the example, is focused on the clothes, he or she may well forget the step and treat the platform as if it is part of the level floor. If the platform floor and that of the rest of the shop floor is similar, with identical carpeting, for example, then the shopper's expectation that the floor is level and there is no step will be incorrect. The person may well fall at the step if he or she fails to notice it.

If the deliberative consequences of the mapping process meet our expectations, event 3, we begin the selection of appropriate behavior—route and speed selection and so on (event 4). If the expectations of the cognitive model are not met—if the steps look icy, for example—then we move to a knowledge-based level and consider whether to proceed or abort the trip. A decision to proceed again leads us to event 4, the selection of appropriate behavior. This is the equivalent of solving an equation containing several terms and may be conducted at the skill, rule, or knowledge level depending on the circumstances. The scanning will have provided values for some

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of these factors—the fixed and variable conditions extant on the stair. However, powerful regulatory, motivational, and physiological pressures will be controlling them.

Conforming to cultural norms is an example of a controlling pressure—avoiding physical contacts with others on a stair and obeying traffic rules, for example. Another factor might be a trip urgency, which would govern speed, overtaking, and the choice of an appropriately short route. Distractions, fixed or mobile, in the field of vision could be affective—trying to maintain visual contact with the subway train at the foot of the stairs, for example, to see if the doors are still open.

Personal, physical, and psychological factors could be influential; weariness or wearing high heeled shoes might mandate a route with a handrail, and so might timidity, infirmity, or personal preference. And, finally, the route selected might be affected by the direction from which the stair is approached and the ultimate direction to be pursued.

Meanwhile, movement toward the stair continues. Just before the first step is taken, a further scan usually occurs. This first step location scan, event 5, is a close-up fixation looking down on the first step, to locate it accurately in space. Frequently at this point, there is a noticeable hesitation in the forward movement before the first step is taken, accentuated by the inevitable change of horizontal speed that must occur. Evidently locating the tread accurately and placing the foot on the first step is a matter of some care, particularly for the elderly, the very young, and the physically handicapped.

After this rather deliberate first step, the gait relaxes into the normal rhythmic meshing of feet and steps, event 6. After a few steps (if ambulation is normal, event 7), a further scan (event 8) usually occurs to monitor the fit of the mesh. This process is repeated at regular intervals until a final scan is made to locate the intersection between the last step and the level plane.

The monitoring scans are a continuation of the conceptual scans, used to detect new information as it becomes available—as new areas enter the visual field, and as changes occur in the fixed and variable conditions, particularly changes in the movement of people. From observations of people ascending and descending stairs (Templer 1974), we find that people scan a stair carefully about once for every seven steps taken unless it is a helical stair. Seven steps is about 6 feet (1.8 m) of horizontal distance. The longitudinal spacing between people at the limit of unobstructed movement on stairs was found to be about 4 feet (1.22 m). So it is interesting to note that people space themselves at less than a comfortable scanning distance apart. Under these conditions, perhaps they scan more frequently.

Remarkably few observable scans occur on helical stairs, possibly because on the helical stair, the direction of the tread is constantly changing as the stair moves around the center from which it radiates, a movement that requires the pedestrian to maintain acute and steady attention. Perhaps on these stairs, the eyes are fixated on some mid-distance point on the stairs ahead, and this concentrated scan is broken only once or twice during the whole traverse in order to look ahead or down.

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During the monitoring scans, the stair is searched for impediments to travel (people, objects on the stair, ice, damage, and so forth). Any obvious impediments will induce a regression back to make the appropriate behavioral choice (event 4). If there are no impediments, the advance will continue (event 6), unless the trip is complete.

During the whole process while advancing on the stair, ambulation is constantly monitored (event 8). If gait continues to be normal, we continue to advance. If a loss of balance is detected, or a trip or slip or other event that may cause a loss of balance, then gait modification and fall avoidance reactions will be triggered.

5.6.3 Attention and Inattention

We adjust our gait precisely to match what our mind tells us about the stair: where the treads and risers are located, how large they are, and so on. Our learned mobility skills translate this understanding into actions. But what if the understanding is flawed?

Our understanding of the stair is dependent on the picture we have of it when we last looked at it (or sensed it by whatever means we have). If our understanding is wrong, then either we have not been paying sufficient attention or have been paying attention but have misunderstood or misread the stairs, so the implication of these two possibilities should be considered independently.

Ambulation on a stair takes place usually in a mental atmosphere with a degree of alertness and awareness of the environment but not to the exclusion of any more interesting or significant thoughts. It is something like background music that every now and again crowds into our full consciousness.

Those whose attention wanders can be divided into two groups: those whose judgment is immature or impaired by drugs, alcohol, senility, or mental illness, and those whose judgment is normal but whose attention is distracted for the moment. There is not much that one can say about the former group except that our evaluation of their actions, as with the klutz, must be fair. Even drunks have rights. A drunk may fall on the stair because the stair is inherently unsafe, not because he or she is drunk. As Judge J. Heydenfeldt opined in a significant ruling in 1855 (Robinson v. Pioche, quoted in McNamara 1967, 267): "If the defendants were at fault in leaving an uncovered hole in the sidewalk of a public street, the intoxication of the plaintiff cannot excuse such gross negligence. *A drunken man is as much entitled to a safe street, as a sober one, and much more in need of it"* (my emphasis).

Those whose attention is distracted and at least for a moment or two, completely neglect to look where they are going and at what they are doing may lose synchrony with the steps, and a loss of balance may be imminent.

Information about the stair or the place we are walking through is gathered during eye scans of the area ahead or of anything that catches our eye and interests us. These scans are coupled with regular glances down at the surface on which we are walking (or the steps of the stair). The frequency and duration of these glances is related to how regular, even, and generally safe the surface appears to be. Walking on a concrete sidewalk that is clean, dry, and

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in good condition may engender a relaxed awareness with few glances at the ground.

A stair with generous treads and comfortable risers, which is in good condition and is well lit, is somewhat more demanding of our attention than walking on the level, particularly as we approach it and establish a gait that meshes with the riser-tread geometry. This may require several glances down. Then as the rhythm is established, we relax into periodic glances down. If we detect any signs of gait instability, a glance down occurs to locate the steps and to correct the gait.

The steeper the stair is and the smaller the tread, the more attention that must be paid to the step to ensure that the feet are located safely. Small children, elderly people, and those with poor vision or balance problems may focus constantly on the steps of steep flights. They will make scans of the environment up ahead only occasionally. The pattern of scans and glances is therefore adjusted to suit the perceived stair conditions, with the frequency and duration of the step glances based on some sort of mental risk analysis.

A misstep or a fall may eventuate when the glance and scan process fails to warn that our feet are getting out of synchrony with the steps or that there is some potential hazard up ahead—a broken tread or a torn carpet. The process fails when the information on which we are acting does not conform to the actual relationship between feet and steps. Perhaps our information is out of date (we have not noticed that our gait is becoming out of synchrony with the steps) or perhaps we have misread or misunderstood the step information.

Information that is out of date suggests that the glances are too infrequent or, expressed in another way, that the stair user is not paying sufficient attention to the steps. His or her thoughts lie elsewhere, or he or she is overconfident. Overconfidence would suggest a faulty behavior pattern that would lead to many falls and might be symptomatic of other ills. Similarly, a pattern of routine inattention would hardly be normal. This suggests that inattention is unusual for normal people. Therefore, we should look for the reasons or causes for this distraction.

Certain stairs and their environments provide an attractive nuisance, to use the legal term that describes why children are drawn to swimming pools and other potentially hazardous places. The stair user's attention is drawn away from the steps and toward something that is more interesting or informative. Is this distraction or inattention the same as carelessness? It might be in individual cases. What if it is a quite usual response at a particular point on a stair for people to look away from the steps toward a suddenly revealed interesting view? Isn't the "carelessness" at least compounded by the design of the stair? If such a design encourages inattention and then causes accidents, it can certainly be argued that the design feature increases the risks in a way that can be avoided and therefore that the stair is unnecessarily dangerous.

Two studies (Templer 1979, 1985) examined the possibility that interesting views from stairs may distract people and cause falls. One study concluded that the incidence of accidents on the top three and bottom three steps of the flight is very high. On these high-risk steps, many orientation factor changes occur—route direction changes, changes of view, and very large changes in illumination. The authors

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concluded that at no point should the stair user have to experience simultaneously several orientation factor changes—changes in illumination, view, route directions, and floor surface or level.

The other study found that visual distractions to the side of the user's path of travel were associated with lower incidence rates, suggesting that the presence of visual distractions may increase the degree of caution exercised by the user. Those who are actually distracted are likely to experience a greater number of accidents.

It is on the two or three steps at the top or bottom of the flight that most incidents occur. It is there that attention to the steps is most necessary as one starts to mesh one's gait to the stair or prepares to leave it. It is there, at these (and any other) orientation edges that people are most likely to be distracted as they start to look around to scan the stair or the places to where they will be heading when they leave the stair. The term *orientation edge* was coined to define an abrupt change from the enclosed surroundings of stairway to an open view of a larger space. Such an edge may distract the user, causing him or her to orient toward events, activity, people, or light within the space and away from the stair (Archea et al. 1979, 78). Orientation edges may occur at any point on the stair.

There are obviously interesting architectural implications to this problem of distractions. It suggests that, for the users, the stair itself should be the focus of the visual scene rather than the surroundings.

5.6.4 Misreading the Stair

What about those who apparently gave due attention to the stair but nevertheless fell—those who acted prudently, cautiously, conscientiously, and in every other way normally but still misread the stair? Gait on stairs is wholly dependent on placing our feet with accuracy on each step. To do this, we must know the precise location of the nosing edge and the riser. Then we must step within these very close tolerances. How much tolerance is available? How much precision is required?

For comfortable and safe walking gait facing forward a tread should not be less than about 11 inches (28 cm). If the step is to be traversed, in one pace, it cannot comfortably be much larger than 14 inches (35.6 cm) for a 5-inch (12.7 cm) riser. Obviously, the smaller the tread (and the larger the foot) is, the less space there is for the foot and for placing the foot wrong.

Apparently there is an even more critical tolerance: that between foot and stair nosing. In ascent and descent, the toe and then the heel must clear two nosings on the way to the new stance. Nelson (1973) showed in his laboratory that in ascent, the gap between the stair and the shoe decreased from the first to the fifth step with clearances as small as ⅜ inch (0.95 cm) or less during normal ambulation. A misreading of the step to this extent is enough to cause us to trip. This certainly does not leave much of a margin for error. Why should anyone misread the location of the nosing edge of the step? As will become apparent, there are many traps for the unwary waiting to fool the eye or at least to befuddle the cognitive processes.

Route modification may then take place as conditions change, as new factors concerning the fixed and variable conditions are understood, and as personal motivations alter. If other people are using the

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stair, physical contacts and conflicts must be avoided. Route modifications will involve interpersonal transactions with regard to territoriality, usually resolved through normative behavior.

If some aberrant gait or balance loss eventuates for some reason, then a series of initially involuntary and then voluntary actions will be triggered. These may be successful, leading to some behavioral and gait modification. If there is insufficient time for an appropriate reaction or the reaction is not successful, a loss of balance or a fall may ensue.

5.7 Summary of Findings

The sequential framework of the stair use process, shown diagrammatically in figure 5.19, offers a format for ordering and summing up the findings. And the findings help to fill in some of the unknown terms. (The tentative and limited conclusions from the exploratory study of group movement of stairs are marked with an asterisk.)

1. When people are offered a choice of flights, they use the flight they reached first regardless of whether it is the right or left flight. This applies if the two flights are equally convenient for their entrance location and their exit directions and are similar in other respects.

Route selection

2. On some stairs, age, gender, or race was correlated with the routes taken; however, in general no such relationships exist.

3. The approach direction does not have any influence on the route chosen (although there are some exceptions).

4. Shortcuts across the stair on entry are common when the entry direction conflicts with the general route taken.

5. On stairs without channels, people tend to keep to their right in ascent and descent; however, if keeping right requires the user to take a longer route, the rule is frequently breached. And the greater is the distance that keeping to the right mandates, the greater are the number of people who violate the rule.

6. On channelized stairs, people tend to use the right channel, unless using this channel forces them into taking a markedly longer route.

7. In ascent, in the right channel, people do not keep to their right. In descent, usually they do.

8. People who use the left channel in ascent and descent usually keep to their right.

9.* If the stair is occupied by other people or there are any impediments, users cede the right of way and then take the easiest route—moving farther to the left if the right is occupied.

10.* If the user is part of a platoon whose members reach the stair as a group, then the user and the platoon invade and capture as much space as is available. Usually, however, they give way to pedestrians approaching from the opposite direction if they have the right of way (and have managed to enter the stair before the rush occurs).

11. Handrails are used in half of all journeys and fairly extensively in 25 to 35 percent of all journeys (in ascent and descent, respectively). The location of the rail does not appear to affect route choice.

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STEP LOCATION, THE LEADING FOOT, AND MONITORING SCANS

12. A slight hesitation or even a pause occurs frequently before the first step on the stair is taken.

13. On some stairs, the right foot is used significantly more frequently than the left when taking the first step onto the stair. On other stairs, the left foot is used more frequently. And on some stairs there is no consistent pattern.

14. Except on helical stairs, the number of step location and monitoring scans is remarkably consistent: about one step location or one monitoring scan per seven steps. The age, gender, and race of the subject does not affect the number significantly. On helical stairs, there are fewer scans, suggesting that users concentrate more fixedly on the stairs.

ROUTE MODIFICATIONS AND CHARACTERISTICS DURING TRAVERSE

15. An extensive use of handrails takes place at the beginning and end of each flight.

16. In descent, women are more likely to use handrails than men. And women, when they use handrails, use them more extensively than men do.

17. The extent of handrail use is related primarily to the handrail's location rather than the stair layout or geometry.

18. The rate of traverse is related to age; the older the subject is, the slower is the rate of traverse. Gender and race are not significantly associated with speed on stairs.

19. Based on observations (from other studies) for stairs with risers (R) from 5 to 7 inches (12.7–17.8 cm) and treads (T) from 10 to 16 inches (25.4–40.6 cm), the multiple correlation equations for rate of ascent V_s that fit the data best are, in vertical feet per minute,

$$V_s = 76.98 + 2.106R - 2.543T$$

and in vertical meters per minutes,

$$V_s = 23.47 + 0.253R - 0.305T$$

20. As a rule, a pedestrian who is balked by another or by any other impediment immediately changes route.

21. Taking shortcuts at landings is standard behavior; few pedestrians take the long route around landings.

22. Most changes of route (that are unconnected with the actions of other users) occur at landings.

23. Many people switch channels at landings when this shortens the total journey on the stair.

24. Shortcuts just before leaving the stair occur frequently if the exit directions differ from the main route taken on the stair.

25. A final scan to locate the last step is common practice.

26. Exit directions are strongly associated with the final route taken on several of the stairs. However, in most cases this simply indicates consistent behavior, not that the exit direction affects the path taken.

CONGRUENCE AND LACK OF FIT

27. Stairs that have a zigzag layout are more likely to induce conflicts than dogleg stairs, and dogleg stairs are more likely to induce conflicts than straight flight stairs. Helical stairs are likely to produce the greatest number of conflicts.

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28. Dextral dogleg stairs and dextral helical stairs are likely to produce fewer conflicts than their sinistral alternatives.

29. A flight whose layout is confusing will generate a more confused pattern of movement than a more clearly understandable layout.

30. Where stairs are wide and without channels, users are likely to choose the shortest route.

The findings corroborate the deductions from the evidential patterns of stair erosion. People generally respond to stairs in characteristic and predictable ways. Many individuals continue to act idiosyncratically, of course, but on stairs this is exceptional behavior. Most people are motivated to adhere to certain simple conventions that permit this environmental component to be shared with others. If the stair and its vicinage give no guidance or when the stair layout is unfamiliar or fits these needs poorly, confuses people, or sets the individual's needs against the social conventions, the results are still predictable. Then the use pattern evinces a lack of coherence and organization of the sort necessary to make a stair usable by many people simultaneously without conflicts. On the other hand, the predictability of human responses to stairs, particularly the patterns of movement, can be put to work and fed back in the design process.

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6 HANDRAILS, GUARDRAILS, AND BALUSTRADES

6.1 HANDRAILS

Handrails help to reduce the incidence and severity of stair accidents. Miller and Esmay (1958) found that in 75 percent of stair falls that they investigated, there were no handrails at the place where the fall originated. Jones (1963) noted that half as many stairs in the accident group of his study had handrails compared to the sample group. McGuire (1971) concluded that 16 percent of all stair accidents can be attributed to missing handrails. And Wheatley (1966) stated that "poor railings caused a substantial proportion of all stair accidents."

For the elderly, the absence of stair handrails is especially hazardous. Sheldon (1960) found that 44 percent of the stair accidents of elderly people might have been avoided if there had been adequate handrails and illumination. Svanstrom (1973) found that 18 percent of the stairs on which accidents had occurred had no handrails. He also noted that in 33 percent of accidents involving people over 60, there were no handrails; for people under 60, only 14 percent of accident stairs had no handrails.

The findings of Carson and his colleagues (1978), however, ran counter to all the others in a surprising way: they found that the absence of handrails was not related to increased accident rates, and when

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they partitioned the data into critical incidents (where no injury was sustained), and accidents (where severe or moderate injuries were sustained), critical incidents occurred on stairways with handrails four times as often as they occurred on stairways without handrails. Also, they found that accidents occurred with approximately the same frequency whether there was a handrail or not. Nevertheless, they concluded that "when handrails are present they reduce severity, or, if they had been present, they would have reduced severity."

Another study (Templer et al. 1985) also raised questions about the role of handrails. Higher incidence rates were found for people who "used the handrail to pull themselves up in ascent or for guidance and balance in descent." The authors surmised that "those who needed to use the handrail to pull themselves up may initially have been more vulnerable and thus had more incidents." In other words, they may have been people with less gait stability, and in the study, this was consistent with older subjects. So this same group might have had an even higher incidence rate if no handrails had been present. The authors suggested that "those who merely used the handrail for guidance and balance may have been lulled into a sense of security that masked some of the risks involved in descending stairs."

Carson's study and the others suggest that injury severity is reduced if a handrail is at hand for the victim to use; if there is no handrail available, any injury is likely to be more severe. They do not tell us anything about the use made of the handrail in the event of a fall, however. We do not know whether there are (or are not) fewer accidents, and perhaps less injurious accidents, on stairs with handrails because people use them or because, even if they do not usually use them, during a fall they are able to grab the handrail and abort or limit the fall.

6.1.1 Do People Use Handrails during Stair Use?

Providing handrails for stair use is no guarantee that they will be used. In fact, in one study of handrail use on five stairs (Templer 1974), 57 percent of the descending stair users did not use the rail at all, 7 percent used the rail minimally (an occasional touch), 16 percent used the rail more extensively, and only 18 percent used the rail extensively (for most of the journey). In ascent, the pattern was similar: 64 percent did not use the rail, 11 percent used it minimally, 15 percent exhibited some use, and 10 percent extensive use. There was some indication that handrail use correlates with increasing age and that women use handrails more than men do. The study indicated that different patterns of handrail use on different stairs were clearly related to the stair layouts. Where the stair handrails were inconveniently located and would force the stair user to take a significantly longer route, handrail use decreased. There was no evidence that users select routes to be closer to handrails.

6.1.2 How Can Handrails Help to Abort or Mitigate Accidents?

In a study of eighty-one stair accidents in Canada (Hay and Barkow 1985, 116–121), only 25 percent of those who fell were using the handrail at the time, and of the seven who fell the farthest (more than ten steps), none was using the handrail. If handrails were available to these people (and some sort of rail was available in 87 per-

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cent of the sites), why were they of no use once the fall started? Their study does not address the question of whether the victims were able to use the rail.

The shortcomings of the studies and the ambiguous nature of the findings raise questions about the ability of handrails to abort falls. This suggests that we should look at the circumstances that may affect our ability to use handrails during an incident. Someone who uses the handrail has a fair—but not certain—chance of aborting a fall and avoiding injury. The chances are only fair because the magnitude of the fall forces may be greater than one's ability to maintain one's grip, the body's attitude during the accident may render it impossible for one to maintain a grip without the twisting motion's damaging one's wrist, or one's reaction time after the onset of the balance loss may be too slow to permit one to tighten one's grasp in time.

If, however, one was *not* using the handrail at the onset of the accident, then the probability that the handrail can be used to help abort or diminish the consequences of the fall is reduced because of the increase in several potentially affective factors:

1. The victim may not be able to reach the handrail. This depends on the location of the handrail, where the victim is at the moment when the grab takes place, and what the victim's body dimensions are.

2. Can the victim grasp the rail during the fall? Are the reactions fast enough to permit the victim to initiate and complete the grasp before it is too late? Is the victim agile enough to complete the action during the physical contortions of a fall? Has the victim the physical agility (with either hand) to complete the action with the necessary precision during the fall? Is the distance of the handrail from the wall sufficient to permit the grasping hand to complete the action? Is the shape of the handrail adequate for a strong grip?

3. Can the victim maintain a grip on the rail during the incident? Is the victim's grip physically powerful enough to handle the magnitude of the forces present during the fall? What are the magnitude of the forces at that moment? What is the victim's body's attitude during the grasp on the handrail? Does this cause any twisting of the wrist? Are the handrail's shape and height adequate to enable the victim to maintain a firm grip? Is the material from which the handrail is made adequate in terms of slip resistance so that the hand will not tend to slip off the rail? Is there any foreign substance present that might affect the coefficient of friction?

In summary, there are three types of information that must be considered:

1. The victim's body dimensions, agility, reaction time, and physical strength.

2. The characteristics of the fall, the body's attitude, and the magnitude of the forces transmitted.

3. The handrail location, height above the nosing, shape, distance from the wall, and slipperiness.

6.2 Handrail Height

Handrail height is usually measured vertically from the stair nosing to the top of the rail. An appropriate height for handrails depends on the purpose and use to which they are put. The main purpose of the stair handrail is to prevent a loss of balance, to help one regain balance, to help one pull

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oneself up a stair, or for directional guidance and stability for those with visual and balance deficits. In each case, one must identify the forces involved and how they can be most effectively transferred between the rail and the body.

The nature of handrail use in descent differs from ascent use. Generally in descent, the hand is slid down the rail in a continuous motion to give the user a sense of security and for some greater postural stability. In ascent, the handrail is grabbed at regular intervals and used to help pull the user up the stair and to give extra postural stability. The use of the rail in an attempt to abort a fall introduces another affective condition that must be considered when deciding on an appropriate height for handrails.

Several approaches to deciding the limits for handrail height have been taken in the past. First, a height has been chosen that places the rail in a position where it can be easily and comfortably reached. Second, a height can locate the rail where it can maximize the bodily strength used to resist forces generated in a fall. A third approach used what might be described as a test under simulated fall conditions. Kvarnström (1977) used a laboratory trick stair with steps that would fall apart, causing test subjects to trip or fall. The stair was fitted with handrails at 23.6, 29.5, or 35.6 inches (59.9 74.9, or 90.4 cm). As a result of 830 tests, they concluded that the highest rail—35.6 inches (90.4 cm)—seemed to be the best.

6.2.1 A Comfortable Height

For comfort, the argument (presented by Chaffin et al. 1978) is that in descent the rail should be no lower than the knuckle height, with arms at the side of a ninety-fifth-percentile person—33.4 inches (84.8 cm). From observation, they concluded that this height should be measured at the midway point of the tread, so they calculated that for a 34-degree stair with a 10.5-inch (26.7 cm) tread, the minimum height at the nosing should be 30.5 inches (77.5 cm). With a height lower than this, taller people will have to bend toward the rail to use it or let the hand trail behind the body when descending, conditions that are uncomfortable and may tend to increase instability.

The minimum height argument assumes that the user is standing close to the stair rail. As Pauls (1982) has pointed out, the farther one is from the rail, the farther one has to reach, and (theoretically) the higher the rail must be set. The centerline of a 97.5th-percentile male—74 inches (1.9 m) tall—with arm outstretched horizontally to grip the rail would be 25.7 inches (65.3 cm) from the rail. Therefore, the rail would have to be set at shoulder height, 58.7 inches (1.5 m) above the tread nosing, obviously a ridiculous height. If the rail is to be useful, for comfort or in an emergency, for the 95th-(or 97.5th-) percentile person who is not walking by the rail, then the rail must be higher than the 30.5-inch (77.5 cm) knuckle height Chaffin et al. recommended.

For comfort in ascent, Chaffin et al. argue that the hand forces and torques exerted by the hand decrease as the angle of flexion is increased. The lower the shoulder height is, the larger is the angle of arm flexion necessary to grasp the handrail. Therefore, they conclude that handrails should be set no higher than 33 inches (83.8 cm) from the nosing if one is to limit

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arm flexion to no more than 90 degrees (for a fifth-percentile female). Ninety degrees is chosen as an upper limit on the assumption that shoulder extension greater than this will be uncomfortable and tiring during ascent. As Maki and Fernie (1988) point out, this assumes that the elbow will be kept straight, unnecessary even for a grabbing motion.

6.2.2 Stairway Fall Models and Handrail Height

There is a demonstrable relationship between the height of a handrail and our ability to transfer the forces involved. In the fixed-axis rotation model, the body loses its balance, perhaps as a result of a misstep, and rotates on an axis about the ankle still in contact with the ground. The destabilizing moment ($W \times dw$) about this ankle is due to the body weight (W) and the horizontal distance (dw) between the body centroid and the ankle. To prevent a fall, a stabilizing force must counteract this moment. The ground reaction force transmitted from the foot to the body via the ankle muscles provides a stabilizing moment. However, the handrail can be used to increase the magnitude of the stabilizing moment ($H \times dh$). In this model, the body is viewed as an upside-down pendulum rotating about the ankle as a fulcrum.

In the case of slip type falls and the latter stages of misstep falls, the action is now too complex to be modeled by a fixed-axis (pendulum) rotation. The body center of gravity may move down as well as forward, and the body may rotate. In this case, use of the handrail may help to prevent falling by providing vertical (Hv) and horizontal (Hh) forces and a stabilizing torque ($H \times dh$). The magnitude and direction of these forces and moment applied to the body from the handrail depend on the orientation and position of the skeletal segments of the arm and the muscle activity in the shoulder, elbow, wrist, and hand.

6.2.3 A Height to Maximize Stabilizing Forces

Maki and Fernie suggest that there are five types of falling motions, and five stabilizing forces and moments that handrail use must contribute to counteract these falling motions:

1. Forward rotation, countered by maximum backward moment (P1).
2. Forward translation, countered by maximum backward force (P2).
3. Downward translation, countered by maximum upward force (P3).
4. Backward rotation, countered by maximum forward moment (P4).
5. Backward translation, countered by maximum forward force (P5).

Of these, they opined that forward rotation is most dangerous in terms of injuries and therefore that the backward moment is the most important parameter for an effective handrail. Therefore, they decided to test six handrail heights (measured to the center line of the rail) to see which were most effective. For the tests, they used a 1.75-inch (4.45 cm) diameter handrail set at a slope of 33 degrees mounted on a cantilevered column bolted to a piezoelectric force plate. They concluded that the optimum range of handrail heights for young subjects lay between 36 and 38 inches (91.4 and 96.5 cm) and for elderly subjects, between 36 and 40 inches (0.91 and 1.03 m). They also asked the subjects to indicate a preferred handrail height for comfort. If a handrail height is uncomfortable or awk-

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ward, they argued, people may be reluctant to use it. They found that the mean comfortable height was approximately 36.5 inches (92.7 cm).

In a later study, Maki, working with another group of researchers (1985, 355–359), used the same experimental technique for subjects on stairs with a 41-degree and a 49-degree pitch. The results were much the same as in the earlier study. They concluded that the pitch of the stair should not affect decisions on handrail height.

The logic behind the tests is a new departure, and the experimental methods were ingenious; however, further work is necessary. In these studies, the subjects did not ascend or descend stairs; they stood stationary on a two-step stair holding onto the handrail and were asked to imagine themselves walking on the stair. They were then instructed to "push forward along the handrail," then "pull backward along the handrail," then "push downward toward the ground," and finally to "pull upward away from the ground." The tests were conducted with the subjects facing down the steps, simulating descent only, and they used their right hands only. They chose where to stand relative to the rail.

It is questionable whether push or pull forces conducted with the subjects stationary are as significant for handrail height decisions as a height that is most effective during a fall. For someone descending a stair without using the handrail, it might be better to choose a height where the handrail can be grabbed quickly. Also, even if a 36.5-inch (92.7 cm) rail is best for the push or pull forces with the subject stationary, at the outset of a fall, the victim may drop as much as 7 inches (17.8 cm), a whole step, before "an answer of will" will occur and the victim grabs the rail. If the victim has fallen 7 inches (17.8 cm), then presumably the pull or push forces will be different from those at the recommended 36.5 inches (92.7 cm). The handrail height may now be effectively 36.5 + 7 = 43.5 inches (110.5 cm), assuming that the body's center of mass (and the hand on the rail) have not moved forward much during the fall. This suggests that before we can adopt new handrail height recommendations, we should conduct tests that are dynamic and where questions of reaction time and effective heights for fall abortion can be explored.

None of these studies deals with the special problems of children or with the relationship between handrail height and where one stands on the stair. Various proposals have been made to locate a child's rail a foot (30 cm) or so lower than the adult rail, but these proposals are not based on any experimental work. Jake Pauls (1986, 6) has recommended a height of 24 inches (61 cm) for children's handrails. Kevin Lunau (1986), on the basis of anthropometric data, has suggested that, to allow for children from ages 4 to 15, the child rail should be 21.8 to 28.7 inches (55.4–72.9 cm). Pauls's recommendation seems to be a reasonable compromise for places where children of all ages may be present; Lunau's recommendations are useful for places such as kindergarten and other schools where the handrail can be located to suit the needs of the specific age group.

6.2.4 Conclusions

The work of Maki and Fernie suggests that 36 to 40 inches (0.91–1.02 m) may be an effective handrail height for counteracting the forces present in descent falls. This

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challenges the 30.5 to 33 inch (77.5–83.8 cm) maximum recommended by Chaffin and others (for ascent). Furthermore, descent falls are the major cause of injury, so if one must choose between an optimum height for both ascent and descent, a height that is most effective for descent is the preferred choice.

6.3 Handrail Size and Geometry

Handrails must be able to transmit forces and moments to and from the human hand effectively. The forces between hand and handrail have two components, one normal (at right angles) and one at a tangent to the handrail surface. Both components have a significant effect, and a well-designed handrail should maximize both normal and tangential forces.

The tangential component is exercised through friction between the skin of the hand and the handrail surface. In other words, the force generated as one pulls up on a handrail or pushes down on it is conveyed in the linear direction of the handrail through the skin of the hand and the handrail. The magnitude of this force is dependent on the handrail material and texture, the skin of the hand, the presence of any lubrication between them, and the magnitude of the effective normal force (gripping force in this case) that is being applied.

The effective normal force can be thought of as the sum of all of the hand-to-handrail contact forces (fig. 6.1). These forces can be expressed as occurring at the contact points. Maki and Fernie suggest that increasing the congruence between the rail and the hand will increase the contact forces and, perhaps, the effective normal force by increasing the number of finger segments in contact with the handrail. Furthermore, by increasing the contact area, the forces can be spread over a larger area, thereby reducing the stresses and strains on the tissues of the hand. They note that to maximize conformation between the hand and rail, a handrail material with a compliant surface is effective. Those who have examined the question of handrail shape have agreed that a circular shape will maximize tangential forces over a wide range of hand sizes and shapes.

Several researchers have studied grip force (Taylor 1954; Swanson et al. 1970, 149–153; Kraft and Detel 1972, 272–275), examining the various types of grip, including the power grip (fig. 6.2) and pinch grip (fig. 6.3). These studies are not strictly transferable to handrail applications; nevertheless, they provide inferential evidence that the power grip is likely to permit a stronger grasp than the pinch grip. The power grip, by definition, brings all of the finger and hand segments into contact with the handrail, which is necessary in order to optimize the effective normal forces.

The most thorough and recent study of handrail shape was by Brian Maki (1988). He tested round handrails ranging in diameter from 1.3 to 2.0 inches (3.2–5.1 cm); square handrails that ranged from 1.1 to 1.7 inches (2.9–4.2 cm); flat rectangular rails ranging from 0.55 by 1.7 inches to 0.83 by 2.5 inches (1.4 × 4.3 cm to 2.1 × 6.4 cm); vertical rectangular rails, including 2 by 4 inches (5.0 × 10.2 cm) and 1 by 6 inches (2.5 × 15.2 cm); and finally a molded decorative rail. He concluded that the largest stabilizing forces were generated by using 1.5-inch (3.8 cm) circular rails. The smallest forces were generated using the vertical rectangular and the decorative rails. For children, the optimal size should

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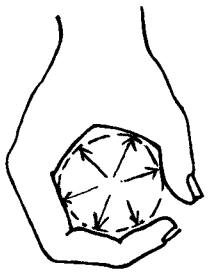
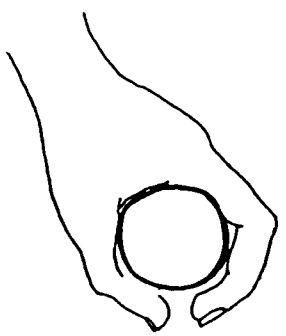
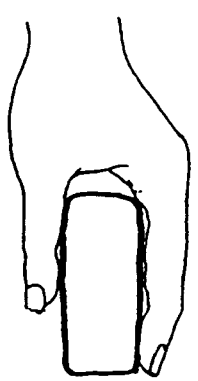


6.1 Handrail normal forces



6.2 The power grip



6.3 The pinch grip

be less—say, 1⅛ to 1¼ inches (2.9–3.2 cm). For grip and sliding comfort, based on preference, the circular and oval handrails had the best ratings; narrow rectangular and decorative railings had the worst.

Handrail shape also must be considered for uses that are not of the grip pull-up or push-down kind. There are times, probably during falls or where a loss of balance has occurred, when one may have to push away from the handrail or pull oneself toward it. By definition, these are normal forces, and, in the former case, the force is usually transmitted through the surface of the hand with no gripping. To minimize tissue damage or discomfort, the load should be spread over as much of the hand as possible. Handrails with elaborate moldings may act to concentrate the forces on an edge of a decorative element and for this reason are undesirable. Ideally, then, a handrail that will meet the condition best will present a large surface area.

When one has to pull oneself toward the handrail, perhaps to prevent a sideways fall in the opposite direction, the pull is transmitted largely through the hand with fingers locked (fig. 6.4) across the rail and protruding down on its far side. The handrail shape to optimize this action is the same as that for the push-pull action except that we are largely concerned with the shape on the outside of the rail. Therefore, the shape must maximize the number of finger joints contributing to the pulling force. Obviously tissue damage or decreased performance will be present also if we must pull against some sharp-edged ornamental molding.

Certain shapes and sizes may force the wrist away from an optimal position to grip the rail. This is particularly important

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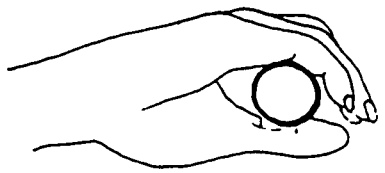

6.4 *Sideways pull*

for the elderly, who may have a reduced range of joint rotation and loss of grip strength. Maki and Fernie have pointed out:

The line of action of the push/pull force should coincide with the natural thrust axis of the forearm, i.e., a line passing from the lateral edge of the elbow to the top of the extended index finger. Handrail shapes and sizes that require wrist extension or flexion (away from the optimal position) to achieve a comfortable (i.e. conformable) gripping position will shift this line of action, resulting in a bending moment about the wrist. This moment must be resisted by the wrist musculature, which may limit the amount of handrail force that can be generated. A handrail with a wide, flat upper surface would seem to create this sort of problem (e.g., oblong with major axis horizontal) and should therefore be avoided.

The handrail must also be considered as part of the stair milieu that may be affected during a fall. People will continue to fall on stairs, so the handrail as part of the stair is a potentially injurious element. If the handrail could be recessed in some way so that it is unlikely that a person falling toward the side of the stair would strike it, then from this viewpoint the shape would not matter. However, handrails that are recessed and will satisfy the needs of the disabled have yet to be developed, and the extant codes and standards explicitly prohibit their use.

A handrail that is not recessed is a potential source of injury. Any sharp edges may cut the hand that slides over it quickly, and a sharp edge is also obviously likely to cause trauma if it is struck by the head or any other part of the body. Similarly, decorative moldings may tear the flesh or act as a blunt instrument to cause injury.

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For injury prevention, then, the handrail should be designed to reduce the force of an impact and to be free from edges or projections. For energy attenuation after an impact, the surface should be large and soft. No studies tell how large or how soft the rail should be, however.

Summing up, then, a 1½-inch (3.8 cm) round handrail is most effective for gripping; however, it is not the best shape for the forces exerted when pushing away from the rail, and it is not the best shape for injury reduction unless it can be designed to attenuate the forces of impact.

6.4 Handrail Materials

The factors that affect the choice of appropriate materials for handrails—friction, tactility, resilience, surface and structural integrity, and appearance—can influence comfort and safety, and comfort probably also influences safety. A rail that is uncomfortable to use because of its shape or tactile qualities may discourage or even prevent use.

6.4.1 Surface Friction Characteristics

When an object is slid over the surface of another object, the motion is resisted by a frictional force related to the coefficient of friction and the force of the contact. As the hand, or any other part of the body, slides against a handrail, the friction induces a tensile force in the skin. The magnitude of that force is dependent on the qualities of the material of the handrail and the magnitude of the effective normal force. Some materials generate larger frictional forces, and rougher surfaces generally engender larger frictional forces than smoother surfaces.

The coefficient of friction between skin and the handrail will be affected, to an extent that has yet to be determined, by temperature, humidity, and any lubricants that are present. Friction increases with increasing load forces and apparently increases with increasing contact even between skin and certain materials such as polyethylene (Chaffin et al. 1978).

The selection of materials with an appropriate coefficient of friction for the ambient environmental circumstances is not merely a question of comfort but is imperative for safety and for injury reduction. A handrail that will become too slippery may actually cause falls if the user is leaning or pulling on it. A handrail that is too abrasive may discourage people from using it and may cause abrasions, avulsions, and lacerations when some part of the body is forcibly moved over the surface. To avoid trauma, materials should be selected to minimize the frictional forces; yet materials must be chosen that will not tend to slip out of the hand.

There are few data available to help us make intelligent trade-offs between too slippery and too rough. Most handrails seem to be designed to be as smooth as possible. This may be particularly hazardous out of doors where precipitation is an obvious possibility as a lubricant, but the danger is also present indoors and wherever any materials may act as a lubricant—fine powder or dust, humidity, or even the sweat of labor (including that of climbing the stair).

Maki tested several materials that can be used for handrails: birch with a matte varnish finish; birch with a glossy varnish finish; birch with a sand and paint mixture;

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chrome-plated steel; enameled steel; vinyl; acrylic vinyl with a dimpled texture; and an aluminum tube covered with a ¼-inch (0.64 cm) sleeve of low-density polyurethane foam. He found the chrome, the acrylic vinyl on a flat metal undersurface, the foam, and the sand-paint rails poor choices for helping people generate stabilizing forces and moments and similarly in terms of user ratings of grip and sliding comfort. He recommended the glossy varnish, the enameled steel, and the vinyl.

The automobile steering wheel provides a useful parallel for considering the forces that may be generated. The wheel must provide us with a firm grip, particularly when making very tight turns at very low speeds. Under these conditions, our hands may easily slip off the highly polished surface. However, a relatively slick surface is needed so that when we let the wheel recenter itself after a turn, it can slip through our fingers without generating any perceptible heat or abrading the skin. The surface characteristics of the wheel may not be critical for most cars, but it is interesting to note that leather- or plastic-covered wheels have become the norm for racing and high-performance cars where the risks of a slippery wheel are great. There are obvious lessons that can be learned from this for stair handrails. Automobile steering wheels increasingly are padded today, to serve two functions. If the wheel is held in a firm grip, the contact area between hand and wheel is increased as the material is compressed into a congruent relationship with the hand. This has the effect of increasing the coefficient of friction but also of increasing the effective normal force that can be exercised and, by spreading the comfort area, of reducing the strain on the tissues.

The padded steering wheel may well be a useful model for the stair handrail. The material can be relatively smooth with a low coefficient of friction, but the coefficient of friction (and the grip) can be increased when necessary by simply holding the rail tighter and compressing the padding into greater congruence with the hand. Maki's subjects rejected the low-density polyurethane foam in terms sliding comfort. This might therefore raise questions about the padded wheel concept. However, as he states, the foam was rejected because of the frictional heat generated; the foam was not covered with any material and must have felt rough to the touch. Its grip comfort ratings, on the other hand, were very high. He suggests that the problems with sliding friction (and hygiene) could be overcome by covering the foam with a thin plastic sleeve. Clearly, more development work is needed. He also states that "the problem remains that the force/moment generation for this surface was poor . . . probably due to shearing of the compliant material. This problem could be remedied to some extent by using a higher-density foam and by reducing the thickness of the foam layer."

6.4.2 Resilience of the Handrail

A handrail material that is too spongy or soft will not provide the necessary strength to resist the forces and moments applied to it. It would be as ineffective as the catenary rope handrail that has been used occasionally. As one leans on the rope, it moves away from us and prevents us from deriving stability from it. A soft, spongy handrail might also move under load and provide an inadequate surface to grab. But handrails that are too soft are practically

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unknown. Handrails are usually of wood or metal, perhaps covered with a plastic surface. They present a relatively unyielding surface that has little ability to attenuate the force of a blow. One falls heavily against the typical handrail; the resulting trauma will be no less than that caused by bumping against a tree or a metal post.

Handrails have not been designed with trauma in mind. The concept of injury reduction is not yet part of the stair designer's lexicon of ideas. Is there any reason to prevent us from using less aggressive materials for handrails? A handrail that has an appropriate energy attenuation capability may add to the cost of a building, at least until manufacturers develop materials specially for the purpose. However, these costs must be weighed against the reduced costs of injuries caused by handrails. And the padding required for energy absorption can also be useful in protecting the hand from friction traumas and increase the ability of the hand to grip the rail.

6.4.3 Heat Conductivity

Some materials are good absorbers and conductors of heat, particularly the metals. Handrails exposed to the sun and the cold may become too hot or cold to touch, or they may cause trauma to those people who use them and who suffer from diminished tactile sense (a not uncommon aspect of aging and diabetes). Certainly, at extreme temperatures, these materials will discourage handrail usage.

6.4.4 Surface Integrity

The problems caused by surface ornamentation have already been discussed. The surface of the handrail is often also rendered less useful by awkward fixing brackets that interfere with continuous hand movement along the rail, and some brackets are fixed using bolts that protrude from the handrail in a way that can injure the hand or any other part of the body that hits them.

Finally, the handrail material must retain its original integrity and must be maintained to prevent deterioration. Most materials deteriorate with age, particularly when used outside. Wood becomes brittle and splinters, and ferrous metals become rusted and pitted—conditions that will prevent or discourage handrail use.

6.4.5 Handrail Visibility

Curiously, the literature on stair safety seldom discusses handrail visibility (however, see Alessi, Brill and Associates 1978), and yet the need for visibility seems obvious. Consider, for example, a white-painted handrail fixed to a white wall or a dark wooden handrail to be viewed against a background of similar hue. It may be quite difficult to perceive the handrail with precision during a fall, and this is likely to be a major problem for those with visual impairments. It seems to make good sense that the handrail should be highly visible and stand out against the background.

6.4.6 Conclusions

Handrails should not be slippery or too abrasive. Rails that are lightly padded like automobile steering wheels can provide the correct range of friction characteristics, may enable better grip forces to occur, and are less likely to cause trauma if they are hit in a fall. Handrail materials should not conduct or retain heat to the extent that they become untouchable. Handrails must not be permitted to deteriorate so that their surfaces become splintered or pitted with

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rust. Finally, the color of handrails should be chosen so that they are always highly visible to the user.

6.5 Handrail-to-Wall Clearance

Many model construction codes prescribe a minimum spacing that they will permit between handrails and any adjoining wall or construction element, and some codes also prescribe maximum spacings. These specifications recognize that for the handrail to be usable, there must be sufficient space for someone to be able to grab the rail in an emergency, as well as for normal use. Some codes are written to try to obviate the risk that someone (particularly someone with upper extremity disabilities) will catch a hand or an arm between the rail and the wall. Building codes represent the natural economic cautiousness of the construction industry, and therefore any code provision that adds to the cost of a building is carefully scrutinized by builders and developers. All of these factors have implications for the safety and comfort of stair users.

The space between the handrail and wall must be large enough for the hand to enter and grasp the rail; the bare hand thickness at the third metacarpal (as quoted by Chaffin et al.) is 1.42 inches (3.6 cm) for the ninety-fifth percentile of the population. Gloves may increase this value by 0.2 inch (0.5 cm), to a total of 1.62 inches (4.1 cm), and flexion of the hand will cause an unknown increase in this thickness. This minimum value of 1.62 inches (4.1 cm) is greater than the maximum permitted by some codes and permits no clearance between the wall and knuckles. Chaffin et al. recognize this and have suggested that another 0.63 inch (1.6 cm) should be added for this, bringing the total clearance to 2.25 inches (5.7 cm). This recommendation does not take into account the situation when the wall has a rough, abrasive surface or when the rail has to be grabbed in an emergency.

The minimum handrail-to-wall clearance is based on the handrail's being used from above in a reasonably leisurely fashion. In the event of a potential fall, the victim may attempt to grab the handle from any direction. Insufficient wall clearance may prevent effective use of the rail. The worst-case example of insufficient clearance occurs where the rail is to be grabbed horizontally from the side and the extended fingers strike the wall (fig. 6.5). In this event, there must be sufficient clearance for the length of fingers extended fully—4.9 inches (12.4 cm) for the ninety-fifth-percentile male—plus some clearance, say 0.25 inches (0.6 cm). On the assumption of a 1.5-inch (3.8 cm) diameter handrail, the wall clearance should be no less than 3.65 inches (9.3 cm): 4.9 inches + .25 inches − 1.5 inches. In actuality, the action of the handrail in the crotch of the thumb decreases the effective finger length; however, this additional tolerance probably counterbalances the stretch of the tissues as the hand is thrust against the rail.

None of these recommendations has been based on observations of stair handrails in use or during accidents or on any experiments, so although they seem to be inferentially reasonable and certainly based on a logic that is absent in the model building codes, further study is necessary. These recommendations also do not deal with the special circumstances of rough and abrasive wall surfaces adjoining the rail. Such surfaces will require a greater

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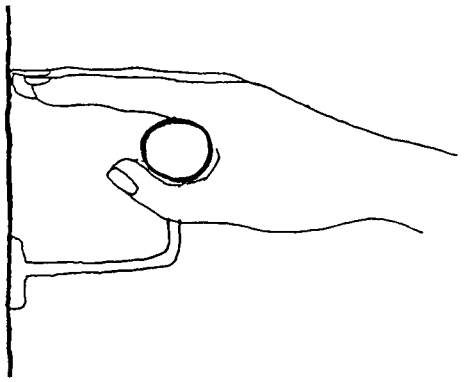

6.5 Horizontal stretch

clearance, and if they are likely to be hit at any time, particularly during a fall, they should not be used.

Before leaving the question of wall clearance, we must address the risk of injury (particularly for those with disabling conditions) from catching the arm between the wall and the rail. The expressed danger is that this may occur during a mishap, resulting in a dislocated shoulder, a fracture, bruises, or cuts, and it is held that this is more likely to occur with larger wall clearances (although obviously not with very large clearances). Some codes in fact prohibit wall clearances in excess of 1.5 inches (3.8 cm) to prevent this from occurring. Maki and Fernie (1988), on the other hand, suggest that although there may be some risk of the arm's getting caught in this fashion, this may prevent a more serious accident from occurring. None of the literature documents actual cases of this sort of injury, so the problem may be more apparent than real.

The model building codes generally discuss handrail location in terms of stairs that are less than 44 inches (1.12 m) wide, stairs that are 44 to 88 inches (1.12–2.24 m) wide, and stairs that are greater than 88 inches wide (2.24 m); the choice of these dimensions is based on a 22-inch (55.9 cm) wide module. Most of the codes permit the provision of only one rail if the stair is less than 44 inches (1.12 m) wide; some permit one rail if the stair is 88 inches (2.24 m) wide.

No one can force stair users to use the handrail. Nevertheless, if there is to be some connection between stair width and the provision of handrails, one would expect stair width to be limited by how far people can reach to grab a handrail in the event of an accident. For example, for a stair for which only one handrail is to be provided (a doubtful provision at the best of times), one might expect the stair width to be limited to the grasping reach of, say, a 2.5th-percentile female. Assuming a 36-inch (91.4 cm) high handrail, this would place her centerline no more than 23.4 inches (59.4 cm) from the center of the rail (Diffrient et al. 1974). Assuming a 7.2-inch (18.3 cm) width for half of her body, then the stair from the wall (assuming that her shoulder brushes the wall) to the center of the rail should not exceed 30.6 inches—7.2 inches + 23.4 inches (77.7 cm). If the handrail is set 3.65 inches (9.3 cm) from the wall and the rail is 1.5 inches (3.8 cm) in diameter, then the distance between walls should not exceed 35 inches (89 cm): 30.6 inches + 0.75 inches + 3.65 inches.

By the same logic, if a stair has handrails on both sides set 47 inches (1.19 m) apart from centerline of rail to centerline of rail,

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either or both rails can be reached by the 2.5th-percentile female. And if two rails are to be provided but only one rail is to be within reach (say, one each for up and down traffic lanes), then this double-lane stair should be no wider than two 35-inch (89 cm) lanes, or 70 inches (1.78 m).

Once the stair exceeds 47 inches (1.2 m), then 2.5th-percentile female stair users can use only the stair rail closest to where they are walking. Also, it becomes possible to walk in a location from which the rails cannot be reached without leaning toward them.

Once the conditions of stair width have been set by handrail location, then considerations of stair capacity and other factors must be taken into account. Most of the model building codes quite rightly require the handrail to be continuous for the entire length of the flight, and several require the rail to extend the equivalent of one tread or more beyond the last riser to enable people to have a rail at hand as they negotiate the first and last steps. This railing projection must be treated carefully so that it does not project into a walkway and become a hazard for people with limited vision.

Summing up, a stair that is 35 inches (89 cm) wide between the walls and with a rail on one side has the maximum feasible width if the rail must fall within the reach of adult users. A 47-inch (1.2 m) wide stair with handrails on both sides is the maximum width for both rails to be always available to adult users. Current codes permit a single rail for stairs up to 44 inches (1.12 m) and two rails for stairs up to 88 inches (2.24 m).

Handrails are not the only means to abort stair falls. They have a long history, but there have been few creative attempts to find alternative and possibly better solutions. One exception is the suggestion from Brill and his colleagues (1974, 76) that handrails may not be of much use and that some sort of cargo netting that one can grab without the precise movements required for handrails might serve more effectively. This idea has not been examined, developed, or evaluated.

6.7 Guardrails

Stair handrails and guardrails are needed for very different purposes. A guardrail is one of several ways of preventing people from falling over the edge of a landing, platform, balcony, stair, ramp, and so on. A stair or ramp handrail serves to help people keep their balance, provides guidance for people with impaired vision, reassures some people who use stairs, helps people pull themselves up in ascent, or aborts or limits falls of those who have lost their balance.

A handrail is usually too low to prevent people from falling sideways over the edge, because of the low minimum handrail heights permitted by the model building codes. So for stairs, ramps, and escalators with handrails but no edge protection, other means must be provided to obviate this risk. One of many solutions is to provide an additional rail (at guardrail height) above the handrail.

Falls from relatively low heights are frequently serious. In Snyder's sample (1977), 14 percent of free falls from 4 feet (1.2 m) or less were fatal. Chaffin and his colleagues (1978) attempted to examine the relationship between the height of a fall and the severity of injury using the Abbreviated Injury Scale (AIS) developed by the American Medical Association, the Society

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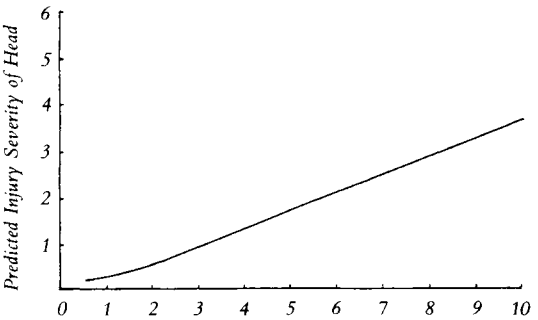
of Automotive Engineers, and the American Association for Automotive Engineering. The AIS rates the severity of a fall on a scale from 0 (no injury) to 6 (untreatable). They concluded that any rating greater than level 1, which will produce no threat to life, little or no permanent impairment, and require minimal medical treatment, is unacceptable. Using head impact velocity, peak acceleration, and an injury severity predicting curve as defined by Snyder, Chaffin et al. generated the graph in figure 6.6. On the basis of this, they recommended the use of physical barriers when fall distance exceeds 4 feet (1.2 m), and the use of fall warning systems when fall heights exceed 2 feet (0.6 m). The authors clearly had misgivings about these recommendations, and it is difficult to understand why fall distances of 2 feet (0.6 m) cannot be avoided or protected, particularly when one considers the abilities of children, the elderly, people with impaired vision, those with balance problems, and the rest of us when we inadvertently slip, trip, or stumble near an edge.



6.6 *Injury severity graph*

The danger of a fall over an edge is not only dependent on the height but also on the impacted surface. A fall of 2 feet (0.6 m) onto rocks is likely to be more serious than a fall onto a padded carpet. Nevertheless, any fall is risky, particularly to the elderly, whose skeletal structure tends to be brittle.

The model building and fire codes in this respect do not go far enough to protect life and limb. Around openings, they mandate the use of guardrails that are at least 42 inches (1.07 m) high, but they permit several curious exceptions. They usually allow a lower height—36 inches (91.4 cm) typically—if the drop is only one floor high, and they require only handrails—usually only 30 to 34 inches (76.2–86.4 cm)—for stairs and escalators.

The logic behind these code decisions is opaque. Snyder has shown that people who fell less than 20 feet (6 m) landed on their heads 76 percent of the time. However, people who fell more than 20 feet (6 m) landed on their feet 63 percent of the time. In relatively short falls, the head is more likely to be injured than in the higher falls. Therefore, there is no justification for lower guardrails for these lower heights.

For stairs and escalators, the codes are mute about guardrails, no doubt assuming that the handrails will serve as guardrails. There is a limited logic to support this view. Certainly most falls on stairs follow a trajectory within the stair; however, in a significant number of cases, the victim overbalances and topples sideways over the rail into the well below. This is not surprising bearing in mind that, for the victim, the stair and escalator handrailing is relatively higher at the point where the fall starts than at a place a few steps down toward which the victim is falling. Furthermore,

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the physical demands of stair use may cause a loss of balance. In a recent court case in Florida, the victim apparently fainted at the top of an escalator, fell sideways and over the moving handrail to the floor below, and was seriously injured.

Stair rails should not be perceived as providing guardrail protection unless they are high enough, a solution that would limit their effectiveness as handrails. The open sides of stairs and escalators must be designed to prevent the possibility that people will fall sideways into the well. Providing a guardrail is one way of satisfying this imperative.

The choice of an effective height for a guardrail at an edge has been studied (Fattal et al. 1976) using anthropomorphic dummies to simulate various postures of humans as they lean against or walk into a guardrail at a brisk speed. The researchers concluded that the guardrail should be set approximately equal to the height of the centroid of the ninety-fifth-percentile composite male population in the United States—42 inches (1.07 m)—with the subject in a straight posture on a level surface. From the viewpoint of safety, a more cautious recommendation might have used the ninety-ninth percentile—43 inches (1.09 m)—to take into account the dynamics of the increasing stature of the population and to protect people who are more than 6 feet, 1 inch (1.85 m) tall. A ninety-ninth-percentile U.S. adult male is 75 inches (1.9 m).

As the width of the guardrail is increased, the risk of overbalancing apparently decreases, so Fattal's group suggested a relaxation of the 42-inch (1.07 m) rule where the width of the horizontal guardrail is greater than 6 inches (15.2 cm) and the adjoining interior floor surface is level. They recommended that under these circumstances, the minimum height of the guardrail should not be less than 48 inches (1.2 m) minus B, where B is the minimum width of the top surface of the guardrail. Thus, if the width of the top surface of the guardrail is 10 inches (25.4 cm), then the required height may be 38 inches (96.5 cm) (48 inches less 10 inches). They concluded that in no case should the rail be set less than 30 inches high (76.2 cm).

A final affective factor that should be considered is the danger that people may choose to sit on a guardrail, particularly if it is a wall with a flat top. A loss of balance from the wall obviously may lead to a fall. This type of design is not unusual in transit terminals and other places where there are few seating places, or where the view from the wall overlooks a platform. Even a 42-inch (1.07 m) wall presents little difficulty to someone wishing to climb up and sit on it. A solution is to make the wall or the rail much higher, or impossible to sit on.

6.8 Balustrades

Although a comparatively small number of injuries are caused by people's striking the balustrading during a fall, these can be reduced by avoiding sharp projections or edges or, better, using an energy-absorbing material.

An additional risk of injury may result from a design that can trap a hand, arm, or some other body part during a fall—some sort of wedge-shaped crevice, for example. A special concern of this sort has been recognized for a long time—the risk of a baby's head's becoming caught or a baby's falling through balusters that are too

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widely spaced. One standard (Teledyne Brown 1972, 2–13) requires that any railing system be arranged so that a sphere 5 inches (12.7 cm) in diameter (representing a baby's head) cannot be passed through the system. This is posited on the grounds that, by the age of 2 years in normal child development, children can negotiate stairs unaided. At this point in physiological development, the average child's head exceeds 5 inches (12.7 cm) in diameter. Anthropometric data show that the fiftieth-percentile 2-year-old has a hip depth of 4 inches (10.2 cm) and can still fall through a 5-inch (12.7 cm) space, leaving the child caught by the head. For 1-year-old children who may not be able to use stairs, crawling to a guardrail or a stair is quite a likely eventuality. This suggests that a spacing that is no greater than 3½ inches (8.9 cm) should be chosen (Archea et al. 1979, 65).

A final consideration is a response to some reported accidents. There is evidently some temptation for children and even adults to climb onto guardrails. In a recent case, a young woman apparently climbed onto the bottom rail of a balustrade; this in effect placed the top rail at only 30 inches (76.2 cm) above her feet. She overbalanced, fell to the ground below, and lost her life. Clearly guardrail effectiveness may be dependent on a design that prevents people from climbing on it.

Another infrequent but hazardous situation arises where objects slide or roll under the bottom rail and fall to the area below. There are some industrial and other locations where the probability of this type of event's occurring is substantial. In these places, a toe board should be provided.

6.9 Structural Requirements of Handrails and Guardrails

The safety provided by handrails and guardrails is obviously conditioned by their ability to resist predictable horizontal and vertical loads. Most codes require the system to be able to withstand a test load without too great a deflection. A typical test requires the system to withstand a 200-pound (90.7 kg) vertical load at the midspan of the rail, with a deflection that does not exceed the length of the rail divided by 96. For a horizontal load test, the system may be required to withstand 200 pounds (90.7 kg), measured at the top of the rail at its midspan, with a deflection that does not exceed the sum of the rail height divided by 24 plus the rail length between vertical supports divided by 96. When the load is applied at a vertical support, the deflection may not exceed the rail height divided by 12.

In public buildings, there is a greater danger of panic loading, so a higher standard of structural strength is required. The test load is increased by 50 percent (or 65 percent in some circumstances such as balconies). For one- and two-story residential buildings, the test load may be reduced by 50 percent.

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7 Avoiding the Causes of Stair Falls: Designing for Injury Reduction

If an error is possible, someone will make it. The designer must assume that all possible errors will occur and design so as to minimize the chance of the error in the first place, or its effects once it gets made. (Norman 1988, 36)

7.1 What Causes Falls?

If our cognitive processes and gait on stairs are disrupted or altered, we trip, slip, stumble, or lose our balance. There is good evidence to indict many stairs and their surroundings for causing accidents. On some stairs, or parts of stairs, many more accidents occur than on other less dangerous stairs.

Demonstrating causality for stair accidents is somewhat like that for lung cancer and cigarettes. Human guinea pigs cannot be used to prove that smoking causes cancer or that certain stair conditions cause accidents. However, it can be shown that more people have incidents when certain stair conditions are present, and there are credible explanations why these conditions are dangerous. Hazardous conditions may be obvious or quite unsuspected. Those that are obvious are less dangerous because at least they can be treated with appropriate circumspection. However, the secret defect lies in ambush—unknown, unexpected, and unanticipated. As one scans the list of these known hazards, it is clear that hidden threats constitute the majority of

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the dangerous conditions and probably contribute to the covert dangers of the rest. These defects can be obviated by appropriate design and responsible construction.

7.2 The Way the Stair Is Designed

7.2.1 Inappropriateness of Stairs

Nature of the danger: Because stairs are inherently more dangerous than level walkways or ramps, there are some circumstances in which they should not be used, no matter how well designed and constructed they are.

The elderly have more stair accidents than other people, they are more easily injured than other people, and the consequences of injury are more severe. Therefore, stairs in homes for the elderly and other facilities for this age group are likely to be the locus of injurious accidents.

Decreased agility, mobility, stamina, and reaction time are typical of the aging process; arthritis and cardiovascular impairments tend to affect gait adversely, particularly on stairs, where the energy demands are high. This may manifest itself as a slow and awkward gait, in which people use the handrail as a crutch. The gait gives an appearance of considerable instability, with frequent stops. It is obvious to the observer that the process is taxing and perhaps painful. It is also obvious that this slow-motion gait makes even greater demands on the balance skills than usual and increases the likelihood of a complete loss of balance. There is evidence (Templer et al. 1978, 9) that more stair incidents can be expected from those whose gait is slow and deliberate or unstable and tottering.

Alcohol also may induce similar gait instability, so stairs that lead to bars and other places that serve liquor are likely to have a higher rate of accidents.

Recommendations:

- When this is feasible, stairs should not be the sole means of access or egress, particularly for elderly people and in places where alcohol is served.
- If changes of level are inevitable, alternative means of access and egress, such as ramps and elevators, should be provided.

7.2.2 An Inappropriate Connector

Nature of the danger: Stairs are sometimes located where they will be significantly more dangerous. For example, the dining area in a restaurant should not be connected to the kitchen by a stair (nor a self-service counter with the seating area). The steps may become slippery from spilled food, and the trays that are carried may prevent an adequate view of the stair.

Similarly, the storage department of a factory or a workshop should not be accessible only by stairs. People who carry objects while they use stairs are more likely to fall (Templer et al. 1978, 9). Without a clear view of the steps ahead, the risk of a misstep increases. Heavy objects may affect one's balance, and carrying things may restrict use of the handrails. Food, liquids, and industrial dust may cause slips.

Finally, fire stairs that continue past the external exit floor down into a dead end, such as a basement, are dangerous. In an emergency, people may make a dash down the stairs only to become trapped.

Recommendations:

- If people traveling between two adjacent areas are likely to be carrying articles, the areas should not be linked by means of steps. The change of level should be

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avoided, or the areas should be linked in some other way.

• If there is a likelihood that potentially slippery materials may be deposited on the stairs, the stairs should be isolated from the source of the lubricant.

7.2.3 Hidden Flights: Dangerous Locations

Nature of the danger: Steps are sometimes located where they may not be noticed. People may fall down stairs because they are unaware of the stair. The fall occurs because the steps are not expected, and the victim walks into the stair, trips, or steps into space. This is a special problem for those with little or no vision, deteriorating vision, or pathological vision deficits. It is also a problem where the stair is concealed by the darkness or is not expected.

Miller and Esmay (1958) showed that 8 percent of the victims in their survey had not even intended to use the stairs but had fallen while attempting to find the bathroom in the dark. Others fell after hurriedly opening doors that swung directly over the top steps. The victim may have forgotten where the steps were or that there were any steps, or the steps or stair may occur in a walkway, inside or outside, in an unexpected place.

One solution is to locate stairs out of direct pathways, so pedestrians must make an intentional (if minor) detour to use them. A second solution is to make them as visible as possible by day and night by illumination, color, and other visual contrast techniques. A third solution is to provide a change of floor surface just before the stair. Obviously, this must not itself constitute a tripping or visual confusion hazard. This floor surface should be detectably different to a severely visually impaired person who uses the long-cane technique, as now required by accessibility codes. Finally, where none of these techniques is adequate to prevent visually impaired people or small children, for example, from falling into the stair, the stair may have to be controlled with a gate or a similar device.

The single step—within a walkway, a passage, or in the form of a display area platform in a store—is common and particularly hazardous. The danger is recognized in some building and fire codes, which prohibit flights of fewer than three steps. In practice, however, this wording is either imprecise or is observed in the breach.

The danger is that the step(s) may not be clearly seen because the light is poor, or, even if there is plenty of light, the step may visually merge with the walkway. The latter condition is a special danger to people with impaired vision.

Recommendations:

• For the safety of the severely visually impaired, stairs should be located out of direct pedestrian ways such that pedestrians must make an intentional (if minor) detour to use them.

• Doors by a landing should not open directly onto a flight of stairs.

• Steps and stairs should be located where they may be easily seen before they are encountered. This may mean that night lights and similar permanent illumination must be provided, or it may mean that, in daylight, the steps must be made to contrast visually with their surroundings.

• Single steps should not be built except at thresholds, curbs, and other places where they are customarily found, and even in some of these places, if there is any doubt whether they will be noticed, the best solution is usually to eliminate them.

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• Where it is considered likely that some severely visually impaired people or small children may fall into the stair, the stair may have to be closed off by means of a gate or some equally effective device.

7.2.4 More and Less Dangerous Stair Layouts

Nature of the danger: Many building codes and conventional wisdom suggest that helical stairs, long straight flights, and stairs with winders are dangerous and should be avoided or prohibited for many uses. Despite some attention paid in the most significant stair studies, the position is still not entirely clear. The results of some of the studies are less conclusive than others. Carson and his associates (1978), for example, concluded that stair configuration has no significant influence on the accident rates, but dogleg stairs, and in some locations straight flight stairs, tend to be the locus of more accidents than other layouts. In methodically similar studies with relatively large samples, Svanstrom (1973) and Kinoshita and Nagata (1978), in Scandinavia and Japan, respectively, concluded that straight flight stairs are clearly more dangerous than dogleg layouts. Svanstrom found that straight flight stairs without landings accounted for 52 percent of all accidents (Kinoshita's study 36 percent) but only 29 percent of all stairs (Kinoshita 12.6 percent). Furthermore, Svanstrom found that a much higher percentage of falls on straight flight stairs (57 percent) compared to dogleg stairs (38 percent) or dogleg stairs that wind around the turn (25 percent) were "severe" rather than "minor." Dogleg stairs, in Svanstrom's study, accounted for 63 percent of all stairs (75 percent in Kinoshita's) but had only 37 percent of the accidents (54 percent in Kinoshita's). In the same vein, Miller and Esmay noted that straight flight stairs without landings had two and a half times as many accidents as straight flight stairs with landings.

Helical stairs and stairs with winders seem to be relatively safe. Miller and Esmay concluded that no more falls occur on stairways with winding turns than on other stairway types. In Kinoshita's study, 6.6 percent of the stairs on the study were helical, but only 1.3 percent of the accidents occurred on helical stairs.

In none of these studies do we learn much about frequency of use. However, because most of the investigations have been directed at home stairs, it may be fair to conclude that in similar locations, the frequency of use may be much the same for each type.

If straight flight stairs are more dangerous, and dogleg and helical configuration are less dangerous, why should this be? One reason might be flight length. Straight flight stairs tend to be very short or very long, and short flights are the locus of more accidents. Another reason might be that helical stairs demand closer attention and therefore visual caution. On straight flight stairs, on the other hand, the path is clear and uninterrupted, and this might induce a relaxed attention. A third reason may be related to accident severity. In other words, the accident rates may be measuring injury severity as much as incidence; victims of severe accidents are more likely to end up in hospitals, and, as we have seen, straight flight stairs seem to induce more severe accidents. This might suggest that helical and dogleg layouts, by nature, limit the distance that the victim can fall, and therefore the number of severe accidents decreases.

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The basic form of the stair affects stair safety in other ways as well. The layout of the stair may be more or less appropriate for the mass movement of people and for avoiding directional conflicts. Helical and other stairs with treads of variable size, which require special attention from the user, are probably a poor choice for moving crowds. On the other hand, dogleg stairs, the more or less standard arrangement for fire exit stairs, can and do jam up in a terrifying way in stampedes. It is therefore tempting to suggest that dogleg stairs should not be used for required exit stairs, but that would be to assume that every stair is likely to be stormed and overwhelmed by a stampeding crowd. If the whole building egress system has been well considered, this is unlikely to happen. The number of people trying to exit at any time should be no more than the stair can contain with safety. However, for stadia and auditoriums of great capacity, where all the people in the audience are likely to leave at the same time (particularly in the event of a fire), it may be prudent design to avoid dogleg stairs and other configurations where people may become trapped and crushed at a corner or landing during an emergency evacuation.

Finally, clockwise and anticlockwise layouts encourage quite different pedestrian movement patterns. Stairs that ascend in an anticlockwise pattern, such as dogleg and helical layouts, are likely to induce people who are ascending to violate the (U.S.) keep-right norm. They may take a path that will bring them into conflict, particularly at blind corners at landings, with those descending and obeying the rule of the road. There is evidence that these conflicts and actual collisions do occur. Although this is not a reported cause of accidents in any of the studies, good sense suggests that a stair is not the safest place to have to take instant avoiding action. On some layouts, a normal gait may be prevented by the mass movement of a crowd or a collision with someone else on the stairs. The victim may be jostled and fall or may be pushed, carried along bodily, or even trampled.

Recommendations:

- Long straight flight stairs without landings are usually prohibited by building codes and should not be built.
- Dogleg and similar layouts with short flights are safer than straight flight stairs.
- Dogleg, helical, and complex layouts should ascend in a clockwise direction to avoid the generation of conflicting streams of traffic.
- For stadia, auditoriums, and other locations with great traffic volumes, layouts with abrupt turns should not be constructed.
- The stair must be large enough for the anticipated volume of pedestrians.

7.2.5 Too Long or Too Short Flights

Nature of the danger: Throughout the history of architecture, theorists have cautioned against flights that are too long, and most construction codes impose limits to the number of steps permitted in one flight. The research studies, however, provide little support for the need for these sorts of limits. Carson found no evidence of any relationship between the number of steps in a flight and the incidence of accidents. However, in another study (Templer et al. 1978), a significant difference between the high-risk and low-risk stairs in

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the sample was found: the high-risk stairs had fewer than ten steps, and the low-risk stairs had more than ten steps.

Before leaping to the unexpected (and unwarranted) conclusion that long flights are safer, one must examine where most accidents occur. Templer et al. (1978) found that one-third of stair incidents occurred on either the first or last step; an additional 25 percent occurred on the second or next-to-last step; and another 12 percent on the third or third-from-the-last step. So 70 percent of the accidents occurred on the top three or bottom three steps. In this sense, the probability of an incident decreases as the flight length increases beyond six steps. It is therefore a statistical oddity that long flights are safer. It does, however, point to the top and bottom three steps as the locus of incidents and helps to explain why flights of six steps or fewer may appear to be more dangerous.

The most probable reason that the top and bottom three steps are the locus of 70 percent of incidents is that these are steps on which the gait must be adjusted to, or from, that used for walking on the level; and it is also the point on the stair where, as one exits, one is looking around for the next part of the journey and the route to be taken (or avoided).

Even if longer flights are, from the evidence, no more dangerous, are they not the cause of more severe accidents? From Svanstrom's study, the answer is no. There is no statistical relationship between the number of steps and the severity of accidents.

Earlier, it was concluded that straight flight stairs are potentially more hazardous than other layouts and that landings are needed to reduce the risks. Furthermore, good sense tells us that very long flights give some of us the same sense of vertiginous unease that very long escalators cause; landings are necessary for people who are overtaxed by the climb and need to stop and rest periodically.

RECOMMENDATION:

- Special attention must be paid to the design of the top three and bottom three steps in any flight.

7.2.6 THE (DANGEROUS) VIEW FROM THE STAIRS

Nature of the danger: One of the new questions, raised by John Archea and the orchestrators of the NBS (1979) studies, concerns the extent to which the orientation edge and the view from the stairs might distract users sufficiently to cause a misstep and loss of balance. One of these studies (Templer et al. 1978) showed that a high-risk group of stairs had a rich view on one side—a view with many people or conditions to attract the stair users' attention. This group of stairs also had a higher-magnitude orientation gradient, a measure of the cumulative effect of environmental factors that are presented to stair users as they pass from step to step. The factors include changes in lateral, frontal, or overhead views; changes in illumination on the step; changes that require a gait alteration, such as at a landing; and changes of direction of pedestrian movement at the top or bottom of a flight. If the views distract us from attending to gait on the stair, a misstep becomes more likely.

These findings seem to suggest that interesting views from stairs are inherently dangerous and only unadorned, enclosed stair tunnels are safe from the danger. This would be to read more into the findings

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than the evidence provides. For example, it was found that although the high-risk stairs were more likely to have an open, rich view on one side, the low-risk stairs might have been open on one side without a rich view or even open on both sides with a rich view. The problem must be caused not only by attention-riveting views but also by whether they attract our attention to the complete exclusion of alternative interesting scenes.

Second, the problem seems to be related to sudden changes in view as one passes from step to step. The high-risk stairs had very few steps on which only one orientation factor changed and many steps where many orientation factor changes occurred, so it seems that a stair that is open to an architecturally stimulating space and even enclosed by it is not necessarily hazardous unless the view is completely absorbing or is presented only at certain points on the stair in combination with other environmental changes.

RECOMMENDATION:

• As a generality, anything that induces stair users to focus attention on the stair rather than the surroundings increases safety. Where this is not possible, the views should be wide open at all points on the stair, not suddenly revealed at certain places and certainly not only at the top three or bottom three steps by the landings, where most accidents occur.

7.2.7 WHERE IS THE TREAD EDGE?

Nature of the danger: Misreading the stair will set up a cognitive misinformation cycle that may translate into faulty foot placement and an accident. Precise information is needed about the exact location of the front edge of the tread of each step. In ascent, finding the nosing edge is not usually difficult because it is close to the eyes and because both risers and treads are visible. In descent, the tread edge, even for those with perfect vision, may be effectively camouflaged because of the step design.

Misreading the location of the tread edge in ascent may cause a trip or understepping where the foot slips off the upper tread; in descent, it may also cause a trip (catching the heel on the nosing edge) or overstepping (perhaps with the foot slipping off the step). All of these events are dangerous and may cause falls.

In a common design failure, the treads seem to merge together. The risers cannot be seen, and the stair looks like a ramp (fig. 7.1) because there is no visual contrast between adjoining treads. All of the treads may be black, white, or virtually any other unbroken, even color, and in certain lights, the nosing edges visually merge with the treads.

The ability to detect the edge of the tread may also be defeated by inappropriate stair carpet patterns or slip-resistance treatments. Some stair carpets have strong decorative and repetitive patterns that dominate the visual field to the exclusion of everything, including the tread edge (fig. 7.2). At one New York City railroad station (discussed by Mowery 1968, 47–49), the stair treads had been treated with a material consisting of lines parallel to the tread edge. Over a six-week period (until the problem was corrected), more than 1400 people fell on this stair. Apparently they were confused as to which line was the actual edge. The stair in figure 7.3, which also has been given a nonslip surface pattern, is probably almost as confusing as the New York stair.

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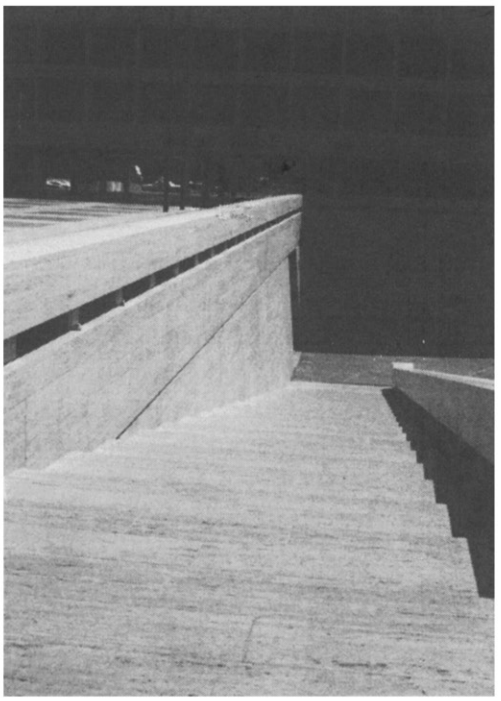
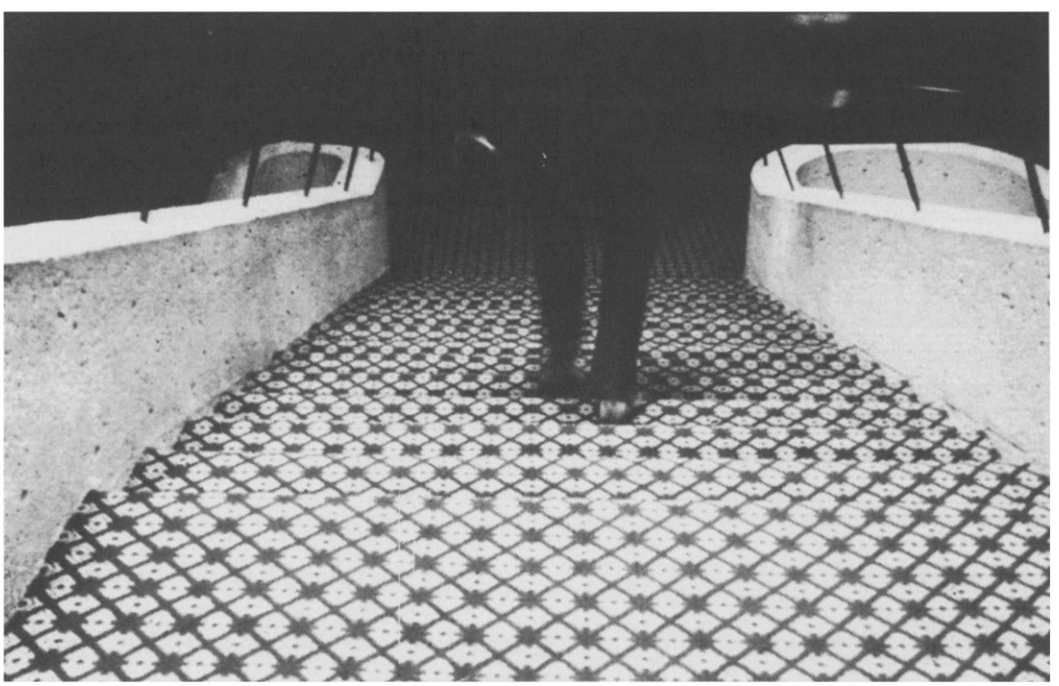


7.1 *A stair that appears to be a ramp*

7.2 *Confusing carpet pattern, reprinted from Archea et al. (1979), 47*



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7.3 Confusing slip resistance materials

The Venetians have found a practical answer. Venice is as much a city of stairs as of canals because every canal is bridged many times. Each bridge is raised to the top of flights of stairs so that the gondolas have room to pass below. Perhaps the ubiquitousness of stairs is the reason that the Venetians developed stairs that are comfortable to use and easy to see. The treads are generous in size, and the riser is expressed on the tread, usually as a 2- to 3-inch (5–7.5 cm) wide stripe. Because the tread is usually dark in color and the riser is often of a light-colored travertine, the nosing is easy to see without any danger of confusion. Another alternative, used by Sir Edwin Lutyens probably for its interesting aesthetic effect and resurrected for the soft stair (fig. 7.4), is to use different tones (or colors) on alternate steps. A contrast between adjoining treads is displayed. This solution must be used with discretion if it is to be effective for people with color vision defects.

It is quite common for technical literature (such as the IES Lighting Handbook) to recommend the use of illumination to solve the problem. It is certainly possible but not easy to draw attention to the tread edge by carefully designed artificial illumination. This is almost impossible to achieve with natural lighting because both the direction and the intensity of the light are constantly changing.

RECOMMENDATIONS:

- Avoid the use of flooring and carpet patterns and abrasive strips that may be visually confused with the edge of the nosing.
- Increase the visual contrast between adjoining treads. This may be achieved by a modest change of tone.

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7.4 *The soft stair*

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7.2.8 Stairs in a Bad Light

Nature of the danger: Our ability to walk on stairs is contingent on sufficient illumination to permit us to see the stair clearly. It should be no surprise to learn that poorly illuminated stairs are dangerous, as many reports and studies have confirmed. Yet Carson et al. (1978) found that about 95 percent of the residential stairways in their survey had light levels below the 20 footcandles (215 lux) recommended by the Illuminating Engineering Society for Stairways at that time (Kaufman and Christensen 1972, 9–99). However, the researchers did not report the percentage of the stairs that met the building code requirements. If they had, they might well have found that most of the stairs complied with the extant codes. Most codes require a minimum lighting level of only 1 footcandle (10.76 lux), one-fifth to one-twentieth of that recommended by the IES today. The IES handbook recommends a range of 10 to 20 footcandles (108–215 lux) for commercial, institutional, residential, and public assembly interiors and 5 to 10 footcandles (54–108 lux) for industrial settings. The choice within the range is governed by the "observer's age, importance of speed and/or accuracy, and task reflectance."

Who is right: the IES, which is not known for recommending low levels, or the codes, which tend to take a lot of convincing before they will accept modifications that may add to the cost of buildings? The Carson study produced no statistically significant findings on illumination but certainly some results that were indicative. The study found that at light levels above 8 footcandles (86 lux), the accident rate was about 11 percent. Below 2 footcandles (22 lux), twice that required by most codes, the accident rate doubled to about 22 percent. This provides at least prima facie evidence that levels above 8 footcandles are twice as safe as those below 2 footcandles.

The Carson study found that the distribution of illumination also seemed to be an affective factor. They found that on many of the stairs, the distribution of illumination varied greatly, giving large gradients. For example, on stairs with light levels between 2 and 8 footcandles (22 and 86 lux), the stairs with low gradients—in other words, with a fairly even level of illumination—had no accidents; those with high gradients had a 32 percent accident rate. This would suggest that a relatively even level of illumination is as important as sufficient light and that shadows falling on the stair should be avoided.

The IES also draws attention to the problem of glare. The natural response of the eye to a bright light in the field of vision is to contract the pupil to limit the amount that will fall on the retina. As a secondary effect, this is rather like lowering the illumination level of the rest of the visual scene. If stair users have a glaring light source in front of them, the accommodation of the eye will make it more difficult for them to see the stair; it is as if there is much less light on the stair. Silvers (1972, 17–25), for example, found that a glare source of 5 footcandles close to the central axis of vision resulted, in effect, in lowering the surrounding illumination to 1 percent of its original value.

A final aspect of stair illumination that affects our ability to see the steps clearly is the surface reflectance—the ratio of the amount of light reflected by the surface to the total falling on the surface. In principle,

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the darker the color of the surface is (or the more light that it absorbs), the less light is reflected from it. Therefore, the greater the absorptance of the stair surface, the greater the illumination that must be provided.

RECOMMENDATIONS:

- Adequate illumination, either natural or artificial, must be provided. The IES recommendation of 5 to 20 footcandles (54–215 lux) for most applications seems to be much more realistic for stair safety than those minima permitted by most building codes.
- The illumination should be reasonably constant over the whole stair, and shadows on the steps should be avoided.
- Window and artificial light sources should not be placed where the stair user must include them, and the steps, in the same direct field of vision.
- In terms of reflectance, the IES recommends 21 to 31 percent for floors.
- If the stair is located where there is any risk that someone might stumble into it unexpectedly, then permanent supplementary artificial illumination should be provided.
- The switches that control the stair lights should be placed sufficiently far from the stair so that there is no risk of a person's falling while reaching for the switch; similarly, three-way switches should be used at the top and bottom of the stairs.

7.2.9 Risers and Treads

Nature of the danger: The dimensions of risers and treads control our gait, comfort, and the probability of accidents. Gait is affected by the height of the riser, the depth of the tread, and the combination of the two. Where the tread size is below 11 inches (28 cm), people descending are impelled more and more to adopt a crabwise gait, with their feet twisted sideways so that the tread can accommodate the whole or most of the foot. This is an awkward gait in which stair users must keep stepping over their own feet and crossing their legs as they take each step.

The more the foot is twisted sideways, the more the foot, in liftoff and in descent, is forced into an unnatural lateral, rolling motion much the same as occurs if we turn our ankle while stepping into a hole. People with mobility and balance disabilities may choose to bring both feet down onto the same step each time to avoid the awkwardness of this gait. If the stair users try to keep their feet facing forward, they may risk slipping off the edge of the step. To avoid this, they may try to keep the heel as far back on the tread as possible where it may get caught against the riser or the nosing.

Very large treads are also difficult to negotiate. As the tread size is increased, a point is reached where it cannot be traversed comfortably in one pace. At this point, one is forced into a dot-and-carry-one gait pattern as if one had one lame leg. The left leg (say) makes the descent (or ascent) onto the next step and the right leg is moved to the front of the same step, rather than onto the next step as is typical on a normal stair. As the tread is increased further, more than one pace on each step will become necessary.

As the dimensions of risers are increased above about 7½ inches (19 cm), using the steps becomes increasingly physically demanding. In ascent, this extra effort probably translates into a greater risk of tripping over the nosing edge. In descent, as the risers are made higher, it becomes increasingly difficult to perform the one-leg

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balancing act that is characteristic of going down stairs. Ultimately a point is reached where the stair user will decline to descend forward and will turn the body and feet sideways or descend backward as on a ladder. For ladders also, the rise is limited by human abilities. The rungs are usually spaced not more than 12 inches (30.5 cm) apart (in fact, the British Standards Institution, 1984, sets the minimum as 22.5 cm—8.9 inches—and the maximum as 25.5 cm—10 inches). Therefore, each foot must be raised 24 inches (61 cm) to mount to the next rung. This height is close to the maximum that the thigh can be elevated.

As the riser height is decreased below about 5 inches (12.7 cm), the stair becomes more and more like a ramp in appearance while still demanding close attention by the users. Where the riser is very small, the gait becomes uncomfortable, and one is tempted to take two steps at a time. As Blondel ably demonstrated so long ago, if the dimensions of risers and treads are not related mathematically to the measures of human gait, then the resulting stair will not match the natural and comfortable characteristics of gait, and the result will be an unnatural and awkward rhythm.

All of these conditions are likely to generate an aberrant gait pattern and increase the probability of an accident. There have been no laboratory studies of stairs with risers less than 4.6 inches (11.7 cm) or goings greater than 14 inches (35.6 cm). Stairs with these very gentle slopes are most likely to be used for garden steps.

RECOMMENDATION:

• The upper limit for riser height, the lower limit for tread depth, and the best combination of dimension for risers and treads for the most usual circumstances in buildings have been established (see table A.4).

7.2.10 PROJECTING NOSINGS

Nature of the danger: The idea of projecting the front edge of the tread beyond the face of the riser below developed long ago. It offers a partial solution to the problem of narrow treads without increasing the overall depth of the tread. It provides, in ascent, extra space for the toe and, in descent, extra space for the heel to tuck in under the nosing projection. Many construction codes in fact require nosing overhangs of ½ inch (1.3 cm) or more, particularly if the going is less than 10 inches (25.4 cm). Clearly there is a conviction that nosings are a necessary safety device, a view supported by a study for the National Bureau of Standards (Templer et al. 1978). For the stairs that were observed and analyzed, it was found that the high-risk stairs (compared to a group of low-risk stairs) had no nosing projections.

Two other research studies that included nosing projections as a variable suggest that they may not always be safe, however. In fact, the larger projections seem to be associated with accidents. Jones (1963) found that 85.7 percent of the accident group compared to 58.1 percent of the sample group had a nosing overhang of 1 to 1½ inches (2.54–3.8 cm). In a recent study for the National Institute of Occupational Safety and Health (Templer et al. 1985), it was found that higher incident rates in descent were associated with greater mean nosing projections. Since the mean nosing projection of the sample was 1 1/16 inch (1.75 cm), it seems that projections greater than this are more likely to be dangerous.

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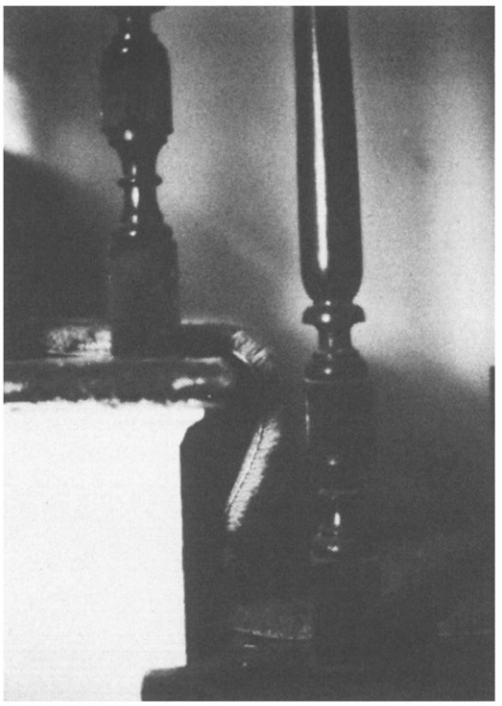
These two studies suggest that nosings greater than about ¾ inch (1.9 cm) may be hazardous. At this point, one might have a suspicion that the cause of the problem is narrow treads rather than large nosing overhangs, but there is no evidence for this conclusion. Why should large overhangs cause accidents? In the NIOSH study, the increase in incidents for the larger nosing overhangs was a factor in descent only. One theory is that larger overhangs are more likely to catch the back of the heel as it pivots upward, and this throws one off balance. This seems unlikely because, although the heel swings up toward the nosing, it also moves horizontally away from the nosing as it pivots, so the cause of these accidents remains in question.

From this discussion, we can conclude that a nosing projection that is no more than about 1 1/16 inch (1.75 cm) adds a modicum of safety compared to a flight with no nosings or a flight with larger nosings.

Abrupt nosing overhang projections, formed by projecting the tread beyond the riser, present difficulties for people with prosthetic feet or legs; the shod foot tends to catch on the nosing. These designs are generally prohibited in codes for accessibility, so the abrupt nosing may soon be a thing of the past. Where the nosing overhang is formed by simply sloping the riser back from the nosing edge, this seems to cause no such difficulties, and these are generally permitted.

Fixing carpeting around steps that have abrupt nosing overhangs is difficult. As a result, carpets are often left to bulge out around the projection without adequate fixing (fig. 7.5). The looseness of the carpet and the lack of definition of the edge of the nosing then become a new hazard.



7.5 *Bulging stair carpet, reprinted from Archea et al. (1979), 36*

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RECOMMENDATIONS:

- Abrupt nosing overhangs, and any overhang greater than 1 1/16 inch (1.75 cm), should not be constructed.
- Nosings of 1 1/16 inch (1.75 cm) or less seem to make steps safer.
- Backward-sloping nosing overhangs should be used rather than abrupt nosings.

7.2.11 TREAD SURFACES AND MATERIALS

Nature of the danger: The appropriate choice of a material for stair treads will be influenced by structural considerations, the type and volume of traffic, appearance, resistance to wear, and, sometimes, chemicals and the climate, ease of maintenance and cleaning, cost, slip resistance, and walking comfort. In terms of safety, research studies have found little to recommend. No materials seem to be significantly safer or less safe than any others if they are properly maintained. Nevertheless, there are known hazards.

A tread surface that is uneven or has projecting joints or nosing strips or a long shag-type carpeting may become a tripping hazard. Loose carpeting or any unstable surface may result in slips, trips, or loss of balance. Tread and nosing materials that do not have an adequate coefficient of friction may become the locus of slips. The surface of treads should have an even and smooth surface with an adequate coefficient of friction. This principle is quite often violated by the presence of uneven joints—in brick stairs, for example—by projecting nosing strips that have been added to increase frictional resistance and by the use of very rough shag carpeting. If any of these project above the tread enough to catch the toe or the heel of the shoe as it swings past in the swing phase, a fall may result.

A second principle requires the tread surface to be stable. It must not be loose or move to any extent under the load of the forces applied to it by the feet. Stairs are not the places for throw rugs or temporary coverings, and carpets must be firmly fitted.

Finally, the surface of the treads and landings (and ramp floors) must have an adequate and uniform resistance to slip forces.

RECOMMENDATIONS:

- The surface of stair treads and nosings should be smooth and even. It should be free from projecting joints and stable under the loads, with no tendency to shift underfoot.
- The surface should have an acceptable coefficient of friction. (Recommended values for slip-resistance coefficient are presented in chapter 3.)

7.2.12 THE WASH

Nature of the danger: The wash is the slope of the tread from riser to nosing edge. A wash is provided to throw water off the stair or to make the risers less high and therefore easier to climb. Intuitively, one might be wary of a significant or obvious slope on the steps for fear of slipping. The one research study that seems to have included the wash as a variable (Templer et al. 1985) concluded that a wash greater than 3/16 inch (0.48 cm), for about 11-inch treads (28 cm), should be avoided. The resistance to slipping is proportional to the slope, so a large wash may require an increased coefficient of friction of the tread surface.

RECOMMENDATION:

- The slope of the wash should not exceed about 1:60.

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7.2.13 Garden Steps

Nature of the danger: Garden stairs may be no more than rough-cut steps on a mountain trail or a stair as monumental, fantastic, and elaborate as any interior stair. A fall on a conventional stair outside is caused by the same circumstances as inside. The question raised here is, What are the characteristics of a safe garden stair?

It is tempting to suggest that all steps and stairs should follow the same standards of design. In principle, that is so. Perhaps a more realistic answer, however, is to say that where a stair appears to be part of a carefully constructed exterior pedestrian walkway system, then the usual standards are expected by the user and should apply. If the steps and stairs are obviously part of an informal rough mountain trail or are, like Michelangelo's *cordonata* leading up to the Campidoglio, parts of an urban-scaled layout, then the users' expectations are attuned to these different circumstances and they can react appropriately. It is the perception of the stair user that must be considered. A dangerous situation develops when people using the pedestrian system do not anticipate a step or steps. This may occur when a designer draws large monumental treads for a piazza. The treads show up as a decorative pattern on the drawing but are not obvious to someone in the piazza.

Recommendations:

- Exterior stairs should be as carefully designed and constructed as interior stairs.
- Grand urban-scale steps or stepped ramps must be made obvious to the users, including people with vision disabilities.

7.2.14 Handrails, Guardrails, and Balustrades

Nature of the danger: Handrails, guardrails, and balustrades are needed for quite different purposes. The purpose of guardrails and balustrades is to protect people from falling over the edge of a platform, landing, balcony, stair, and so on. Handrails serve to prevent a loss of balance, to help one regain balance, to help pull oneself up a stair, and for directional guidance and stability.

Recommendations for handrails:

- Height: Recent research suggests that the 30- to 34-inch (76–86 cm) standard height for handrails found in many U.S. building and fire codes may be too low and that 36 to 40 inches (91.4–101.5 cm) may be better. For children aged 4 to 15, a rail of 21.8 to 28.7 inches (55.4–72.9 cm) has been proposed. For places where children of all ages may be present, a height of 24 inches (61 cm) has been recommended.
- Shape and size: The largest stabilizing forces are generated by using 1½ inch (3.8 cm) circular rails. The smallest forces are generated using vertical rectangular and decorative rails. For children, the optimal size should be less—say, 1⅛ to 1¼ inches (2.9–3.2 cm). For grip and sliding comfort, circular and oval handrails have the best ratings; narrow rectangular and decorative railings have the worst.
- Materials: Handrails should not be slippery or too abrasive. Rails that are lightly padded like automobile steering wheels can provide the correct range of friction characteristics, may enable better grip forces to occur, and are less likely to cause trauma if they are hit in a fall. Handrail materials should not conduct or retain heat to the

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extent that they become untouchable. Handrails must not be permitted to deteriorate so that their surfaces become splintered or pitted with rust. Finally, the color of handrails should be chosen so that they are always highly visible.

• Handrail-to-wall clearance: The clearance between a handrail and an adjoining wall, assuming a circular handrail with 1½-inch (3.8 cm) diameter, should not be less than 3.65 inches (9.3 cm).

• Location: A stair that is 35 inches (89 cm) wide between the walls and with a rail on one side has the maximum feasible width if the rail must fall within the reach of adult users. A 47-inch-wide (1.2 m) stair with handrails on both sides is the maximum width for both rails to be always available to adult users. Current codes permit a single rail for stairs up to 44 inches (1.12 m) and two rails for stairs up to 88 inches (2.24 m).

Recommendations for guardrails:

• Guardrails should be set approximately equal to the height of the centroid of the ninety-fifth-percentile composite male population in the United States—42 inches (1.07 m)—with the subject in a straight posture on a level surface. From the viewpoint of safety, a more cautious recommendation might be using the ninety-ninth percentile—43 inches (1.09 m)—to take into account the dynamics of the increasing stature of the population.

• Where the width of the horizontal guardrail is greater than 6 inches (15.2 cm) and the adjoining interior floor surface is level, the minimum height of the guardrail should not be less than 48 inches (1.2 m) minus *B*, where *B* is the minimum width of the top surface of the guardrail. In no case should the rail be less than 30 inches (76.2 cm).

Recommendation for balustrades:

• The spacing between balusters should be no more than 3½ inches (8.9 cm) in order to prevent infants from falling through.

7.3 The Way the Stair Is Built

Nature of the danger: All the attention to stair design that has been described thus far will reduce stair accidents only if the stair is built properly. In fact, some of the greatest gains in accident reduction can be reaped simply by insisting that stairs be constructed according to the original design and that a reasonable level of precision be present in the finished product. Frequently, this is not the case. Handrails are not fixed firmly in place and pull loose from the wall. Stair carpets break loose from having too few fastenings. Risers, treads, and nosing overhangs are built with little dimensional uniformity.

Dimensional inconsistency—where risers and treads are constructed with heights or depths that vary from step to step—has been identified in several studies as a cause of accidents. Velz and Hemphill (1953) found a 15 percent nonuniformity on all stairs, and 75 percent on stairs where accidents had occurred. Miller and Esmay (1958) found 75 percent nonuniformity equal to or greater than ½ inch (1.3 cm) on the accident stairs and 45 percent nonuniformity equal to or greater than 1 inch (2.54 cm) on the sample group of stairs. The average irregularity on the latter stairs was 1.3 inches (3.3 cm). Jones (1963) found frequent riser height variations in the accident stairs—78.8 percent as compared to

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28.4 percent of the sample group. Svanstrom (1973) found that 39 percent of the accident stairs had a variation in riser height of more than ¾ inch (1.9 cm). Tread depth irregularities occurred in 47.6 percent of the accident stairs in Miller and Esmay's study and only 20.7 percent of the sample group. The average irregularity was 0.6 inch (1.5 cm).

Nosing overhang irregularities were found in 69 percent of the accident stairs by Miller and Esmay (1958) and in only 25.4 percent of the sample group. In Jones's study (1963) the average nosing irregularity on the accident stairs was 0.9 inch (2.3 cm).

The problem is that stairs, if they are wooden (or the original formwork, if they are made of concrete), are often constructed without sufficient care and precision. A second problem is that the top or bottom riser is sometimes substantially different from the rest because the carpenter has not taken into account the thickness of the two floor finishes to be constructed later or because carpet or some other material is placed over the original floor material during alterations.

These dimensional variations are considerable and yet apparently not sufficient to be visually obvious. This is why these poorly constructed stairs are dangerous. The accurate location of the tread edge is critical for safe passage, and the clearance between stair and shoe may be as small as ⅜ inch (0.95 cm)(Nelson 1973). If the nosing edge projects ⅜ inch (0.95 cm) or more beyond (or behind) its fellows or if the riser height is ⅜ inch or more higher (or lower) than the adjoining steps, it is likely to cause missteps or trips. If the tread is smaller than expected, the stair user may step over the edge in descent.

RECOMMENDATION:

• Risers, treads, and nosing projections must be constructed with a high degree of dimensional consistency (and in fact most building codes wisely insist on this). The differences in dimension between the largest and smallest in a flight and between those in adjoining steps should not exceed 3/16 inch (0.48 cm). This is by no means too exacting a standard for contemporary building practices.

7.4 THE WAY THE STAIR IS MAINTAINED

Nature of the danger: It seems hardly necessary to set out the obvious—that stair accidents will result from poorly maintained stairs—yet Velz and Hemphill (1953) found that about 30 percent of the treads in their survey were not in good condition.

Levels of deterioration and damage that might be acceptable for level walkway surfaces cannot be tolerated on stairs; the risk of a serious injury is too great. The greatest danger comes from any structural weakness that may cause any part of the stair to break during use. Nearly as bad is the condition where the treads on the surface material are chipped, torn, splintered, loose, or excessively worn. Of almost as much concern are handrails and balusters that are broken, missing, or loose.

Finally, there is the hazard caused by objects or deposits allowed to accumulate on the stair—toys, articles stored on the stair, water, ice, snow, sand, dirt, grease, and industrial process powders. Svanstrom found that dirty, wet, and slippery stairs were the main reason for 8 percent of accidents, and snow or ice were the main reason for a small percentage of falls. The whole gamut of gait failures may be induced by poorly maintained stairs.

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RECOMMENDATIONS:

- Stairs should never be used as a location for storing objects.
- Stairs must be kept clean and free from precipitation, dust, dirt, and anything else that might act to trigger slips and trips.
- The surface finish of treads (and carpets especially) must not be allowed to deteriorate noticeably.
- Handrails and balustrades must be kept in good repair, firmly fixed, and structurally sound.
- Artificial illumination sources must be kept in good operating condition.

7.5 THE WAY PEOPLE USE STAIRS

Nature of the danger: A study for the National Bureau of Standards (Templer et al. 1978) found that there were more accidents than expected from those who wore shoes with flat soles and no heels. Why this should be the case is not clear. One might expect high heel shoes or boots to be dangerous, but no evidence of this was found. The only other clothing factor that was significant was the length of clothing: there were more incidents than expected from those whose clothing stopped above the knee. However, this was the same as saying that children have more accidents. There were also more incidents from those who were accompanied by one or more people. Again, this probably reflected children accompanied by adults.

In the study, it was found that people change the object of their attention just before a misstep; some were watching other people just before the incident, and some had suddenly changed direction on the stair. All of these acts represent inattention or distraction, which is hazardous behavior.

Finally, it was found that carrying objects on stairs is dangerous. There were more incidents than expected from those carrying articles, regardless of how the items were carried. Svanstrom found that 46 percent of the accident victims were carrying something in their hands when the accident happened; two-thirds carried something in one hand, and one-third used both hands.

RECOMMENDATION:

- Perhaps stairs should carry a message from the surgeon general warning that stairs may be dangerous to health and advising people to proceed with caution, to pay careful attention to the steps rather than other people or things, and not to carry articles while on stairs. This facetious suggestion may even be worth considering in high-risk locations (if these are absolutely unavoidable). Alternatively, these caveats should be made part of safety training programs.

7.6 REDUCING INJURIES FROM STAIR ACCIDENTS

Nature of the danger: Stair accidents can be reduced by intelligent design, construction, maintenance, and use, but this is not enough. This is rather like designing, building, and using cars in such a way that they are inherently safer and less likely to be involved in accidents but not worrying about what happens to the passengers if there is an accident. There is no doubt that the automobile industry has developed cars that are incomparably safer than those of even twenty years ago. Passenger compartments have been strengthened, safety glass is used, seat belt restraints are provided, bumpers and chassis are designed to absorb the energy of moderate collisions, and the

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vehicle interior is padded to cushion the force of the impact when any part of the body strikes it. Furthermore, automobile design is constantly being improved to provide additional safety for the occupants in the event of an accident.

The automobile manufacturers, the U.S. Congress, and the courts recognize that vehicular accidents are inevitable. Cars are now designed to reduce the probability of accidents' occurring. Also, the industry has a responsibility for the passengers even if the accident is in no way attributable to a failure of the vehicle.

Can one say the same about stairs? Have stairs been gradually improved over the years through the efforts of manufacturers and legislation? Have the risks of stair use and the results of stair accidents been minimized? Building code officials may feel that an affirmative answer is in order, and they can point to changes in the codes. Usually stairs must comply with the construction codes in force when they are built, and it is assumed that compliance with the codes will guarantee a reasonable level of safety. This places a responsibility on the codes to be up to date in terms of the known facts. This is not easy because codes set out minimum standards that, for economic reasons, tend to be accepted by professionals and lay people as the standard; exceeding the minimum is sometimes thought of as a deliberate luxury.

Code minimum standards permit the construction of stairs that do not comply with reasonable minimum standards of safety, so in this sense they enforce the construction of unsafe stairs. Furthermore, the codes, the construction industry, and the courts have yet to require protection for stair users who fall. No attempt has been made to develop or mandate the construction of stairs that will minimize injuries in the event of falls. It may be argued that we do not know how to reduce injuries, that there have been no research findings to demonstrate a causal relationship between stair design and injuries or to show that any measures will effectively reduce injuries; and it is true that little research has been directed at stair injury reduction. In the meantime, one can use common sense, intuition, and the model of automobile safety to suggest ways of reducing injuries. Toward this end, the idea of the *soft stair* is proposed. By a careful choice of materials and details, stairs can be designed to obviate certain types of injuries resulting from falls, and to greatly reduce the severity of others.

RECOMMENDATION:

Injuries are caused by the force of the impact of the body, or a part of the body, striking the steps, handrail, balustrade, or walls of the stair or anything projecting into the stair. As a conceptual model for injury reduction, we can suggest that anything that at any place can decrease the force of an impact will reduce the magnitude of any injury. This is a similar model to that used in the design of automobile passenger car compartments. In a car crash, the occupants, as loose objects with their own inertia, act as projectiles within the compartment. Unless they are restrained by seat belts or are flung from the car in a crash, they will eventually lose their inertia only by striking parts of the interior of the car.

The strategies for minimizing injuries to passengers of automobiles involved in accidents are restraint and then energy attenuation. Seat belts and air bags have been the usual forms of restraints. Have restraints

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any practical application for stairs? Technically, it is possible to develop an inertia reel seat belt type of restraint that could be clipped onto a modified handrail so that it could slide up or down and would reel in and out quite freely unless it detected a sudden rapid movement, such as would occur at the start of a fall. Then it would immediately lock up to prevent the rapid acceleration of a fall. Such a belt might be practical for people with mobility and balance problems, but the average stair user would almost certainly refuse to use it. Similarly, it would be possible to fit stairs with air bags that could be triggered by some sort of acceleration sensors, but air bags have not yet proved to be an economic or popular solution even for vehicles.

Because stair falls do not occur within the same range of decelerations as automobile accidents, a third type of restraint, the active restraint, is also often an option. The fall may be aborted by grabbing the handrail or balustrade.

Other restraint systems are possible, but research is needed to examine the practicality of alternative systems. The second line of defense in the automobile interior is created by the removal or modification of anything that might stab, cut, lacerate, or bruise the occupant in the event of a crash. Knobs have been placed in recesses or capped with soft spongy tops; pressed metal edges have been rolled into curves and covered with sponge. Direction indicators, wiper controls, emergency brakes, and other levers are set into recesses or put behind the wheel. The murderous damage from the shards of broken glass of windshields and side windows has been greatly ameliorated with the development and mandatory use of tempered and shatterproof glass.

Are there any reasons why this second line of defense should not be applied to stairs equally? There are technical and economic considerations similar to those that have been debated vigorously in the automobile industry. The only technical reason for any hesitation might be that this is not usual practice today. There are probably additional costs also. However, the cost of building safer and less injurious stairs should not be considered in isolation from the costs of injuries, deaths, insurance, and litigation.

To apply the automobile defense philosophy to stairs, one must visualize a human body falling helplessly out of control with arms and legs flailing about; so one must remove or modify anything that might stab, cut, lacerate, or bruise the victim.

Stab wounds can be caused by the victim's falling against or grabbing some fairly sharp projecting feature. This type of design may be an integral part of some elaborate wrought-iron balustrades, but it may simply be the sharp corner of a stringer (fig. 7.6).

Most cuts will come from bumping up against edges and corners such as those sometimes found on nosings or aluminum nosing inserts. Balustrades and handrails frequently are made from rectangular or square bars or wood sections, and stringers are formed from timber or plates. Frequently, these sections are left with sharp-edged corners.

Lacerations can be caused by falling against any rough surface on the side walls or the treads or balustrade. Commonly walls adjoining the stair are finished with rough concrete (fig. 7.7), plaster, brick, or

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7.6 *The sharp stair*

7.7 *Handrail by a rough wall*

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even wood. Some treads are given a surface akin to a cheese grater under the misguided belief that this will reduce slips. Balustrading may be constructed with ornamentation that will cause severe lacerations to anyone falling against it. Finally the stair, or more usually the balustrading, may have construction bolts and protruding nuts that no one would make contact with in normal stair use, but that may become dangerous during a fall.

Bruises, fractures, and concussions will result from striking against nosing edges, the rods and bars that are typical of many balustrades, square or rectangular handrails, and any other projections. In effect, the force of the fall is absorbed by a blunt instrument.

All of these hostile elements can and should be modified or eliminated from stairs, or at least from the areas where falls may occur. The stair should be free from projecting elements, sharp edges and corners, any rough surfaces, bars, rods, and plates of small section. Instead, smooth, flat surfaces should be used or gentle curves.

These design tactics will lessen the incidence and severity of many types of wound, but severe traumatic injury may still occur even if the body strikes a relatively smooth flat surface with sufficient force. The third strategy in the design of automobile interiors is directed at absorbing the energy of the impact by the use of padding. Just as a stuntman can fall several floors onto a pile of mattresslike devices without getting hurt, the same principles can be used within a car or for a stair.

Most injuries from stair falls are caused by collision with the steps and landings, so the greatest rewards in injury reduction will be derived from softening these—rounding the nosings and reducing the hardness of the surfaces. These measures must be taken with due discretion. The rounding of the nosing must not substantially reduce the size of the tread, and the walking surfaces must not be made so soft as to interfere with a normal gait.

Little research is available to help set out the limits of acceptable and effective softness. However, the future probably lies with materials (or underlayment) similar to those used for tumbling, acrobatics, and judo in gymnasiums. These materials are relatively firm to walk on and, because of their thickness, composition, and resilience, can readily absorb falls from heights. For the time being, we can make use of the ubiquitous carpets and underlayment available, so long as these materials have no adverse effect on gait.

In addition to the steps and landings, energy-attenuating materials should be applied to all the surfaces that a victim may fall against. Walls at the side of the stair or at the end of the landing should be padded, as should any balustrading. Even the handrails should be treated like the steering wheel of many modern cars with a firm but compressible material that provides a good grip but can still reduce the impact of a blow.

Conceptually the soft stair can be realized, and stairs can be designed so that accidents will be infrequent, and injuries minimized.

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8 Liability and Stairway Accidents

The evil that people do lives after them, and so it is with negligent design, construction, and maintenance. Long after a building has been built, an architect, builder, or owner of the premises could face a lawsuit for negligence resulting from an accident. Recent nationwide rumblings about tort reform have highlighted that we are, by any standard, a litigious society. One branch of personal injury cases refers to slip and fall cases. This has become a substantial element within the law of torts. A significant number of those injured in stairway falls find their way to competent legal counsel. Accordingly, it may be useful to have at least an introduction to the law of negligence and other jurisprudential concepts that relate to stairway design.

8.1 Negligence

A person who is guilty of negligence through action or inaction may be liable at law to the injured party for damages. The idea of negligence embraces four factors: (1) a legal duty owed to another, (2) breach of that duty, (3) injury, and (4) injury proximately caused by breach of the duty. It is the responsibility of the injured party, the plaintiff, to show that negligence and injury have occurred and that these four factors were present.

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Those who design, build, or maintain stairs have a duty to adhere to the standards of their professions to ensure that the finished product is not defective. Thus, use of the stairway should not present an unreasonable risk of harm to the user. Philo and Rine (1977, 12–18) define risk as "probability of injury in percentages." A hazard is "a condition or changing set of circumstances which presents an injury potential." Danger, they state, is "the unreasonable or unacceptable combination of hazard and risk. Any risk of serious injury or death is unreasonable or unacceptable if reasonable accident prevention methods could eliminate it." Therefore, one who designs or constructs a stairway must exercise a corresponding duty of care in the design and construction. Similarly, the owner or occupier of premises has a duty to maintain the stairway and approaches to the stairway in a safe condition. However, the liability of the owner or occupier of a building can be rather complicated because of certain peculiarities of British common law still adhered to by many states. Accordingly, the extent of the duty owed may depend on the classification of the injured person as a licensee, invitee, or trespasser.

Some of the duties owed by an architect, builder, or owner are set out in statutes, ordinances, building and fire codes, and the like that specify standards of design, construction, and maintenance procedures. Statutes and safety codes provide standards that if deviated from may be prima facie evidence of defect. For example, many building and fire codes have a requirement for adequate lighting. The person in control of the structure has a duty to ensure that lights are kept in usable condition; however, if the code does not speak to issues of lighting, the owner or persons in control are nevertheless under a common law duty to see that passageways and stairways are reasonably fit for the use intended. If reasonable fitness and safety require the use of lights, then notions of ordinary care require that the duty be complied with. In addition to requirements for lighting, handrails, and the like, building codes deal with many other facets of design, construction, and maintenance of stairways. The content of these codes varies widely among the different jurisdictions. In every case, however, these codes should be considered as minimum standards. Achieving some lesser measure may afford a basis for liability.

The mere occurrence of an accident is insufficient to impose a finding of fault. The predicate for liability is that the accident occurred because the defendant breached some duty owed to plaintiff. For example, if one fails to provide a handrail as required by a local building code or other standard of professional practice, it may be relatively easy to show that the standard of ordinary care (duty) has been compromised. However, compliance with codes or other safety regulations does not always insulate one from liability or accusations of negligence. It is possible to comply with each and every applicable law or code and still be found negligent. Ordinary care or standards of professional practice may impose a duty or responsibility higher than those set by applicable codes. For example, at the board of inquiry into the sinking of the *Titanic,* the ship's owners testified that, although there were not enough lifeboats for the passengers and crew, they had broken

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no laws; they had conformed to the standards. In such a situation, mere compliance with a code may prove an imperfect shield against a suit.

8.3 Proximate Cause

Was a defect in the stairway responsible for the plaintiff's injury? Did the plaintiff trip and fall because of a loose carpet, or did plaintiff merely fail to watch where he or she was going? Although the answers to such questions are usually supplied by a jury, the plaintiff bears the burden of proof of causation by showing that, but for the unsafe condition or defect, the accident would not have taken place.

Quite commonly, the plaintiff will recall little of the fall or accident and can only guess at how the accident occurred. In such situations, an expert witness is often brought in to establish causation.

8.4 Injury

While the concept of injury is a simple idea, what the law contemplates in this regard is damage or injury that is legally compensable. A person who has been injured because of negligence has the right to seek damages from the responsible party. Depending on the jurisdiction and the circumstances, damages most often consist of medical expenses, lost wages, and compensation for pain and suffering. Medical expenses and lost wages are sums certain and are described in the law as special damages. An amount for pain and suffering, however, is not capable of calculation by totaling receipts. Accordingly, most jurisdictions continue to leave to the enlightened conscience of fair and impartial jurors the issue of how much to award for pain and suffering.

8.5 Negligent Construction and Design

Specific legal restrictions on stair design and construction have evolved through statutory pronouncements, codes, and the common law. The failure to observe these standards may result in liability. Courts have imposed liability for improper construction or design in many instances. In general, liability may be imposed where stairways or ramps fail to meet customary construction standards. If the defect was the result of negligent design, the user may sue the architect and builder, as well as the owner, as long as suit is filed within the time period set by the particular jurisdiction (statute of limitations).

8.6 Duties of Ownership

The owner or person in control of a stairway must maintain it in a reasonably safe condition. This duty of care may also extend during the construction phase of a stairway. Once a defective condition has been discovered and before the necessary repairs have been made, an adequate warning placed on the premises is generally required.

A common basis for imposing liability on the owner of a premises is negligent maintenance. This may include a variety of defects, such as broken treads, worn carpets, displaced or broken metal strips, foreign substances on the stairway, unusually smooth tread surfaces, or inadequate lighting.

The mere ownership or control of property does not, however, impose a basis for liability without regard to fault. Liability must be predicated on a duty by those in control of the structure to protect those on the premises against an unreasonable risk of injury.

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A common basis for claims of negligent maintenance is slippery stairway surfaces and defects in the floor covering of stairs. If the plaintiff claims that he fell down the stairs as a result of either, then the nature, identity, description, and location of the defect must be shown. If the steps were unreasonably slick due to some foreign substance, the person in control of the structure may be held liable for failure to remove the substance after he or she learned or should have learned of the defective condition. The mere fact that steps are slippery does not satisfy the elements essential to plaintiff's case. The person in control of the premises must be found at fault based upon a negligent act of commission or omission. For example, a person who slips on a banana peel left on a stairway by another user of the stairs 10 seconds earlier may have no case against the person charged with maintaining the stair. It is doubtful that one has a duty to inspect a stairway every 10 seconds. If, however, the banana peel has turned black with age because it was discarded on the stairway 10 hours before the fall, then a jury arguably could find a breach of the duty adequately to inspect the premises.

An interesting nuance in this area exists where a slippery condition results from natural causes such as ice and snow. Courts are divided on the duty of the owner or occupier to remove or otherwise guard against natural accumulations of snow and ice. Therefore, the duty owed in this area depends on the law of the state in which the injury occurred.

8.7 Notice

An extremely important element in the concept of ownership liability is notice. The owner or person in control of the premises is held to two kinds of notice: actual notice or knowledge and constructive notice or constructive knowledge (that which can be inferred based on the knowledge or actions of a reasonable person). Notice by inference or constructive notice may be a jury question, with consideration given to the nature and scope of the defective condition, the length and time that the condition has existed, whether other accidents of a similar nature have occurred, and so forth. Constructive notice may usually be established if there is sufficient evidence to show that a reasonable person in control of the premises would have discovered the defect in the exercise of ordinary care. The existence of the constructive notice concept vitiates an "ignorance is bliss" defense and may impose a requirement on owners, landlords, and management companies to inspect properties at reasonable intervals.

If the owners or other people in control learn of a defective condition on the property, they must take action to cure the defect or be held responsible to an injured party. Until the defect can be removed or repaired, the owners may be under a duty to warn the users of the problem. This duty to warn may be satisfied by diverting traffic away from the defect, adequately marking the defect to call attention to it, and then effecting repairs within a reasonable time. The duty to warn may exist even where the defect is in no way the fault of the architect, builder, or owner.

8.8 Plaintiff's Negligence

In addition to the duties owed by those who design, build, and maintain stairways, users of the stairs have a corresponding

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duty to act responsibly and to exercise ordinary care for their own safety. Countless negligence claims are defeated by a plaintiff's failure to exercise this duty of ordinary care.

A monetary recovery may be reduced or denied completely depending on the degree of plaintiff's own negligence. For example, courts have denied monetary recovery in cases of defects that were readily apparent to the user. Users are charged with notice of obvious hazards and to that extent are responsible for their own safety. A user is not, however, required to inspect for hidden defects.

A plaintiff who fails to exercise ordinary care for his or her own safety may be deemed contributorily negligent or comparatively negligent depending on the circumstances and the jurisdiction in which suit is brought. If the injuries would not have happened but for the negligence of the plaintiffs, then recovery may be denied completely (contributory negligence). Where, on the other hand, there was negligence by both a plaintiff and the defendant and the negligence occurs at the same time and both contribute to the injury, then recovery may not be barred under the doctrine of comparative negligence. The plaintiff's award is diminished proportionally to his or her degree of fault.

A plaintiff may also be found to have assumed the risk of injury. The doctrine of assumption of risk is not based on notions of plaintiff's own negligence. Rather, it presumes that plaintiff has knowingly and voluntarily assumed the consequences and risk of injury. Consider the case where three steps have rotted at the bottom of a long flight of stairs. The owner of the premises makes arrangements to have the steps repaired but in the interim places a sign at the top of the stair warning people not to use them. The plaintiff sees the sign, disregards it, and is injured when falling through the bottom step. The plaintiff in this situation may be held to have assumed the risk of injury. He or she was aware of the danger and nevertheless proceeded. When plaintiff assumes the risk of injury, recovery may be barred.

8.9 The Expert Witness

Many court cases involve issues that are difficult, if not impossible, for a jury to understand without help. In such cases the services of an expert may be used to educate the jury and the court. Generally architects, engineers, and contractors perform tasks beyond the ordinary understanding of laypersons. Accordingly, it is entirely appropriate for the parties to make use of professionals in the field who offer their opinion, analysis, and testimony. An expert, whether testifying for plaintiff or defendant, breathes life into a case by helping a jury and the court understand the claims and defenses of the parties.

The expert plays several roles in stairway litigation. First, the expert may be used to determine how the accident happened. Sometimes the user has no recollection of the incident or no idea what precipitated the fall. In this situation, the expert may reconstruct the accident based on an examination of the stairway, the nature of the injury, and the position that the victim assumed at the end of the fall. Second, the expert may be used to establish the existence of a defect in design, construction, and/or maintenance. If plaintiff and expert can establish a causal nexus between the fall and injury, then the technical requisites

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of the plaintiff's claim have been met. Third, the expert may be asked to render an opinion as to whether extant codes and standards were violated.

While a juror might view a photograph of the accident scene and have some vague notion that the stairway was too steep, the expert can testify that the slope of a stair is properly determined by riser-tread combinations. Where it may be an easy task for a jury to find negligence in a case in which the sixth step of a darkened stairway was missing, it would be more difficult for a juror in another case to grasp that a defect had been built into the stairway because of negligent design.

The type of expert required in any case depends on the issue or issues being litigated. For example, if the plaintiff bases a claim on negligent design in terms of building codes and standards, the services of an independent architect might be utilized. If a stairwell crowded with shoppers collapsed, perhaps the services of a structural engineer might be brought to bear. An illumination engineer could be useful in a case that turned on issues such as the adequacy of lighting. A biomechanical engineer—one who specializes in the aspects of human locomotion—could be useful in determining causation. Human factors specialists are increasingly used to explain how specific features or aspects of a stairwell and its surroundings interplay with human relations, tendencies, and awareness.

8.10 Conclusion

In every negligence case, the plaintiff bears the burden of proof and must establish each of the elements of the case: duty, breach, proximate cause, and damage. The duty owned by the architect, builder, or other person in control of the premises may hinge on the dictates of prudence, statutes, local building ordinances, and building codes.

A plaintiff must show that the defect in the stairs was the proximate cause of the injury sustained. In establishing both the nature of the defect and the way in which the defect caused the accident, the plaintiff may rely on the testimony of an expert witness. In defense of a plaintiff's claim, the defendant may assert the failure of plaintiff to exercise ordinary care for his or her own safety (contributory negligence) and may also offer an expert to show the absence of either defect or causation.

Ultimate issues of negligence, liability, and monetary damages are usually decided by a jury.

Standards of safety and professional practice change. Professional standards that comply with today's notions of due care may prove woefully inadequate by tomorrow's standards. The propriety of design constantly evolves with advances in the science and art of engineering and architecture. While claims of malpractice are no more welcome in the architectural community than in the medical profession, the threat of litigation provides a constant reminder of accountability and the need to be aware of advances in the knowledge base of their professions.

The compensation claims of workers of the industrial age gave rise to occupational and safety regulations. Product liability suits against automobile manufacturers have had no small effect on improving the crashworthiness of cars. Similarly, litigation in the area of premises liability can have a positive effect on the stringency of safety and building codes and the awareness of building professionals to the duties owed the public.

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APPENDIX
QUICK DESIGN CHECKLIST

This appendix provides a design sequence and a checklist of the information that is useful at various stages of the design process for stairs. For fuller discussions of the recommendations, see the relevant chapters and sections of this book, which are cited here by number in boldface. Some of the appendix tables appear earlier in the book and are repeated here for reader convenience.

A.1 ESTABLISH PRELIMINARY CONFIGURATION

Preliminary selection of stair configuration depends on the floor space available, the floor-to-floor height, the pedestrian movement volumes and patterns, and the groups of people who will use the stair.

A.1.1 STAIR USER GROUP

The potential users may be able-bodied adults, specific handicapped groups, children, the elderly, or all of these groups. The potential use of the stair may be as a means of access and egress; in a public or monumental location, with a large volume of pedestrians; or in a private location.

There are special design considerations for some groups:

- *Disabled:* Provide an alternative access way so those who cannot use stairs are not denied entry.

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• *Elderly and disabled:* For the elderly and some handicapped people, designs that depend only on stair access and egress should be avoided (**7.2.1**).

• *People carrying food, drinks, and supplies:* Avoid placing stairs where people will routinely carry food and drink that may spill on the treads. Avoid stair designs where workers must carry bulky or heavy objects, or anything else that may limit their view of the treads or affect their balance (**7.2.2**).

• *Children:* Stairs for use by children need an additional, lower handrail (**6.2**). The balustrading must be spaced at less than a 3½-inch (8.89 cm) sphere (**6.8**) to prevent the passage of a small child. For control of toddlers, the stair may be closed by a gate (**7.2**).

A.1.2 Factors That Affect Location

• Where large crowds of people will use the stairs (theaters, stadia, fire egress for large buildings), the stair should be located so it does not cause a hazardous bottleneck by making a sudden change of direction—a dogleg stair, for example (**7.2.4**). The stair should be located to encourage continuous direct flow.

• Avoid pedestrian movement directional conflicts at the top and bottom of the stair. Figure A.1 shows a stair leading directly to and across a passage with heavy traffic.

• Avoid direction, view, and illumination changes. Figure A.2 illustrates several potentially hazardous layout conditions—the bottom of a stair where sunlight may blind users or a fascinating view that may distract attention.

• Avoid entering or exit hazards. Figure A.3 shows a door opening directly onto a landing.

• Avoid a configuration that violates the keep-right principle in the United States. Helical flights that ascend by spiraling up to the right, and dogleg and other layouts that ascend to the right, enable those ascending to keep to the right with little effort (**5.3.3, 5.3.4**). This reduces the likelihood of conflicts with those descending (figure A.4).

• Avoid fire escape stairs that continue past the ground-floor egress point down into a basement. These may mislead people during an emergency, drawing them down to a dead end.

• The existing environment may limit the amount of space available for a stair (fig. A.5). If this constraint exists, establish the size of area that is available.

A.1.3 Stair Types and Performance

• *Direction and flow:* The direction of travel that people will take to and from the top and bottom of the stair will be affected by the stair layout, and vice versa (**5.3.2, 5.3.3, 5.3.4**).

• *Stair shape, area, and performance:* The amount of floor space a staircase occupies is related to its shape. Some layouts use less space than others, and some are more effective than others for moving stretchers, furniture, crowds of people, and so on.

A.2 Determine Dimensional Restraints

Stair design in buildings may be governed by several codes and standards. Refer to the applicable building code, fire code, handicapped code, occupational safety and health regulations, Department of Housing and Urban Development Standards, ANSI Specifications, and other applicable codes. The recommendations here are based on research findings, not code requirements.

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A.2.1 Width

Stair width should be a function of comfort, capacity, and reach (handrail availability).

The minimum design width of stairs for single-file use should be 29 inches (74 cm) for a public place. For comfort, about 38 inches (97 cm) is necessary. Side-by-side walking dictates a width between walls of at least 56 inches (1.42 m), a module of 28 inches (71.12 cm). A more comfortable module of 34.5 inches (87.63 cm) dictates a minimum width of 69 inches (1.75 m) (**4.1**).

The stair must be wide enough for the expected volume of traffic. The capacity of the stair is expressed in people per minute per foot (per meter) width. To plan for the expected flow per minute, one must consider the occupancy of the space to be served.

The total occupant load per building floor can be found by dividing the floor area by the occupant density, using square feet per person (m^2/person). Estimates of occupant density per building type are given in table A.1. Dividing the anticipated total occupant load of the floor (say) by the average evacuation time of the people yields the number of people per minute who will pass a point on the stair. For a walkway leading to a stair, table A.2 provides a level of service. Generally only levels 4 to 8 are acceptable. Level 3 may be acceptable for bulk arrival (platoon) situations. However, this should be carefully considered. For the stair itself, table A.3 recommends the use of no levels higher than E. However, to avoid queues' forming, level E should be avoided also and level D used with discretion. Using level E, 13–17 persons per 12-inch (30.1 cm) width of stair per minute, we might use 15 persons per foot width of stair per minute to establish the required width of the stair. This would give the effective width. To allow for handrails, adjoining walls, and so on, another 14 inches (35.6 cm) may be necessary. A stair to evacuate 200 people, who take an average of 2 minutes to reach the stair, must be able to carry 100 people per minute. At a maximum flow of 15 people per foot width per minute, an effective stair width of 6.67 feet (2.03 m) will be required. Based on a module of 28 inches (71 cm), 7 feet (2.13 m) will be a better effective width. Allowing for adjoining walls and handrails, a total of about 8.17 feet (2.49 m) will be necessary (**4.3.2**).

A.2.2 Riser-Tread Dimensions

Table A.4 gives acceptable rise and going relationships based on energy expenditures and potential for safer gait (**2.7**). Riser heights that are more than 7.33 inches (18.6 cm) and goings that are less than 11 inches (27.9 cm) are not recommended. Going dimensions greater than 14 inches (36.6 cm) may also be acceptable, but no research is available to confirm or deny this. In the table, dimensional increments between entries are also acceptable. Applicable codes and standards may differ from these recommendations.

The **riser height** (fig. A.6) is the vertical height of a single step. The **going** is the horizontal distance, in plan, from the nosing edge of a step to the nosing edge of the next adjoining step. The **tread depth** is the horizontal distance, in plan, of a tread. Some codes require a nosing overhang if the treads are small.

Dimensions of adjoining risers and treads must be constructed to be constant and regular.

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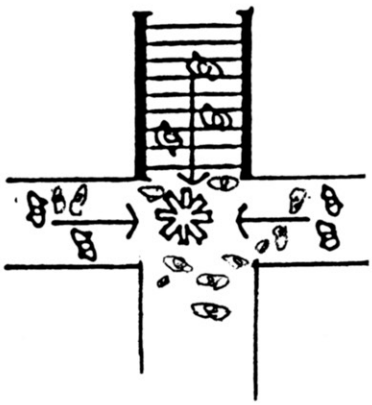
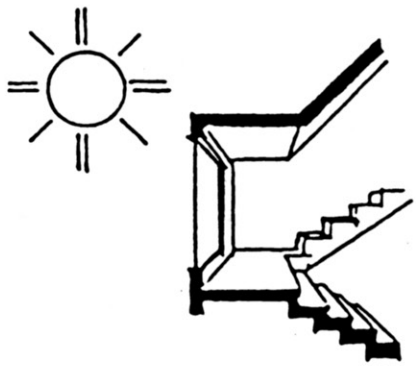
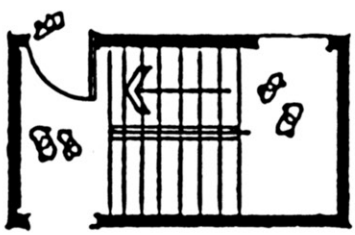


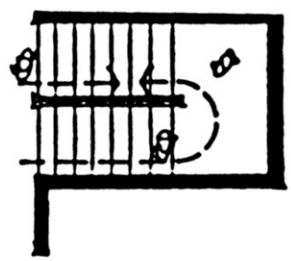
A.1 *Avoid conflicting pedestrian movement directions at the top or bottom of the stair*



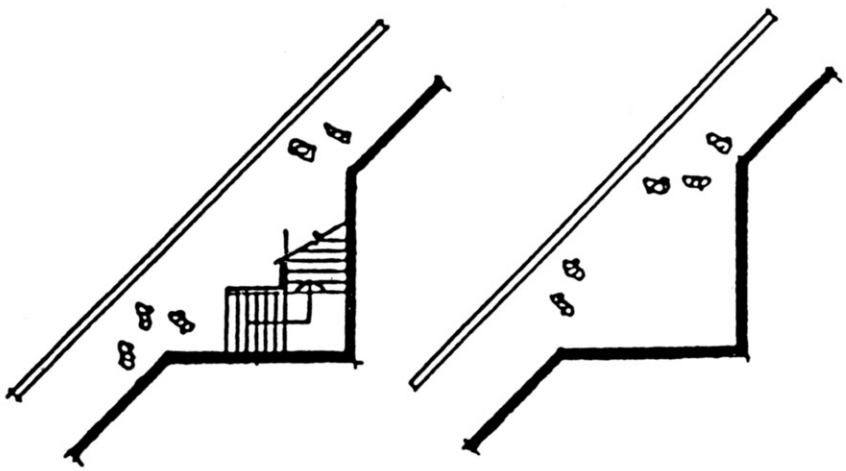
A.2 *Avoid direction, view, and illumination changes*



A.3 *Avoid entering or exit hazards*



A.4 *Avoid keep-right conflicts*



A.5 *Avoid spaces that are too small*

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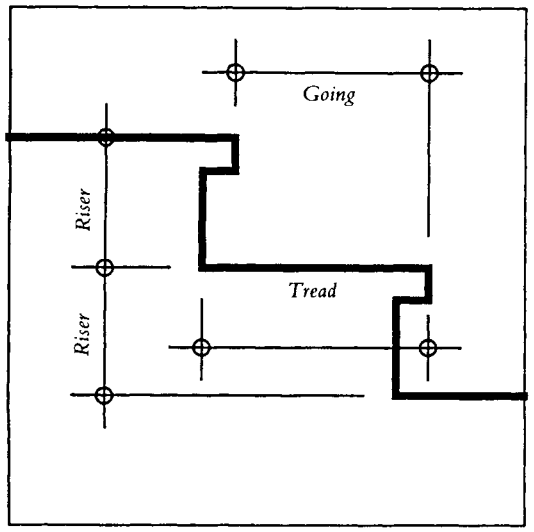

A.6 *Riser, tread, and going*

TABLE A.1

Estimate of Occupant Numbers for Various Types of Building

	Occupant Load		*Maximum Travel Distance*	
Occupancy	*Square feet per person*	*Square meters per person*	*Feet*	*Meters*
Residential	*200*	*18.6*	*100*	*30.5*
Educational			*150*	*45.7*
classrooms	*20*	*1.9*	*100*	*30.5*
shops	*50*	*4.7*		
Institutional, sleeping areas	*120*	*11.2*	*100*	*30.5*
treatment areas	*240*	*22.3*		
Assembly	*15*	*1.4*		
without fixed seats	*6*	*0.6*	*100*	*30.5*
standing areas	*3*	*0.3*		
Business	*100*	*9.3*	*100*	*30.5*
Mercantile			*150*	*45.7*
first floor	*30*	*2.8*		
other floors	*60*	*5.6*		
storage and shipping	*100*	*9.3*		
Industrial	*100*	*9.3*	*100*	*30.5*
Storage	*300*	*27.9*	*100*	*30.5*
Hazardous	*100*	*9.3*	*75*	*22.9*

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TABLE A.2

Levels of Pedestrian Density in Movement on the Level

Average Area per Person, sq. ft. (m^2)	*Characteristics*
Level 1:	*Flow: erratic, on verge of complete stoppage*
2 to 5 (0.2–0.5)	*Average speed: shuffling only, 0–100 ft./min. (0–30 m/min.)*
	Choice of speed: none, movement only with the crowd
	Crossing or reverse movement: impossible
	Conflicts: physical contact unavoidable
	Passing: impossible
Level 2:	*Flow: 23–25 PPM/ft. (75–82 PPM/m), a maximum in traffic stream under pressure*[a]
5 to 7 (0.5–0.7)	*Average speed: mostly shuffling, 100–180 ft./min. (30–55 m/min.)*
	Choice of speed: none, movement only with the crowd
	Crossing or reverse movement: most difficult
	Conflicts: physical contact probable, conflicts unavoidable
	Passing: impossible
Level 3:	*Flow: 19–23 PPM/ft. (62–75 PPM/m), attains a maximum in relaxed traffic streams*
7 to 11 (0.7–1.0)	*Average speed: about 70 percent of free flow, 180–200 ft./min. (55–61 m/min.)*
	Choice of speed: practically none
	Crossing or reverse movement: severely restricted, with conflicts
	Conflicts: physical contact probable, conflicts unavoidable
	Passing: impossible
Level 4:	*Flow: 15–19 PPM/ft. (49–62 PPM/m), 65–80 percent of maximum capacity*
11 to 15 (1.0–1.4)	*Average speed: about 75 percent of free flow, 200–240 ft./min. (61–73 m/min.)*
	Choice of speed: restricted, constant adjustments of gait needed
	Crossing or reverse movement: severely restricted, with conflicts
	Conflicts: unavoidable
	Passing: rarely possible without touching
Level 5:	*Flow: 12–15 PPM/ft. (39–49 PPM/m), 56–70 percent of maximum capacity*
15 to 18 (1.4–1.7)	*Average speed: about 80 percent of free flow, 240–270 ft./min. (73–82 m/min.)*
	Choice of speed: restricted except for slow walkers
	Crossing or reverse movement: restricted, with conflicts
	Conflicts: probably high
	Passing: rarely possible without touching
Level 6:	*Flow: 10–12 PPM/ft. (33–39 PPM/m), roughly 50 percent of maximum capacity*
18 to 25 (1.7–2.3)	*Average speed: more than 80 percent of free flow, 270–290 ft./min. (82–88 m/min.)*

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	Choice of speed: unless stream similar, restricted by bunching
	Crossing or reverse movement: possible, with conflicts
	Conflicts: probably high
	Passing: difficult without abrupt maneuvers
Level 7:	*Flow: 7–10 PPM/ft. (20–33 PPM/m), roughly one-third of maximum*
25 to 40 (2.3–3.7)	*capacity*
	Average speed: nearly free flow, 290–310 ft./min. (88–94 m/min.)
	Choice of speed: occasionally impeded
	Crossing or reverse movement: possible with occasional conflicts
	Conflicts: about 50 percent probability
	Passing: possible, but with interference
Level 8	*Flow: one-fifth maximum capacity or less*
Over 40 (over 3.7)	*Average speed: virtually as chosen*
	Choice of speed: virtually unrestricted
	Crossing or reverse movement: free
	Conflicts: maneuvering needed to avoid conflicts
	Passing: free, with some maneuvering

[a]*PPM/ft.: pedestrians per minute per foot width of walkway; PPM/m: pedestrians per minute per meter width of walkway.*
Source: Pushkarev and Zupan (1975) with flow and speed figures derived from Fruin (1987).

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TABLE A.3

Levels of Pedestrian Density in Movement on Stairs

Average Area per Person, sq. ft. (m^2)	*Characteristics*
Level F:	*Flow: up to 20 PPM/ft. (66 PPM/m), flow attains a maximum, but is erratic*
Less than 4 (0.37)	*with frequent stoppages and verges on complete breakdown*[a]
	Average horizontal speed: shuffling, 0–70 ft./min (0–21 m/min)
	Choice of speed: none
	Passing: impossible
	Queuing at stair entrance: yes
Level E:	*Flow: 13–17 PPM/ft. (43–56 PPM/m), intermittent stoppages*
4 to 7 (0.37–0.65)	*Average horizontal speed: 70–90 ft./min (21–27 m/min)*
	Choice of speed: none
	Passing: impossible
	Queuing at stair entrance: yes
Level D:	*Flow: 10–13 PPM/ft. (33–43 PPM/m)*
7 to 10 (0.65–0.93)	*Average horizontal speed: 90–95 ft./min (27–29 m/min)*
	Choice of speed: restricted
	Passing: impossible
	Queuing at stair entrance: some at higher flow level
Level C:	*Flow: 7–10 PPM/ft. (23–33 PPM/m)*
10 to 15 (0.93–1.4)	*Average horizontal speed: 95–100 ft./min. (29–30 m/min)*
	Choice of speed: restricted
	Passing: impossible
	Queuing at stair entrance: none
Level B:	*Flow: 5–7 PPM/ft. (16–23 PPM/m)*
15 to 20 (1.4–1.9)	*Average horizontal speed: 100 ft./min. (30 m/min)*
	Choice of speed: freely selected
	Passing: restricted
	Queuing at stair entrance: none
Level A:	*Flow: 5 or less PPM/ft. (16 PPM/m or less)*
More than 20 (1.9)	*Average horizontal speed: 100 ft./min. (30 m/min)*
	Choice of speed: freely selected
	Passing: at will
	Queuing at stair entrance: none

[a]*PPM/ft.: pedestrians per minute per foot width of walkway; PPM/m: pedestrians per minute per meter width of walkway*

Source: Fruin (1987).

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TABLE A.4

Range of Rise and Going Relationships for Comfort and Safety

Rise	*Goings*						
INCHES							
7.2	*11*						
7	*11*						
6.5	*11*	*11.5*	*12*	*12.5*			
6	*11*	*11.5*	*12*	*12.5*	*13*	*13.5*	*14*
5.5	*11*	*11.5*	*12*	*12.5*	*13*		
5	*11*	*11.5*	*12*				
4.6	*11*						
CENTIMETERS							
18.3	*27.9*						
17.8	*27.9*						
16.5	*27.9*	*29.2*	*30.5*	*31.8*			
15.2	*27.9*	*29.2*	*30.5*	*31.8*	*33.0*	*34.3*	*35.6*
14.0	*27.9*	*29.2*	*30.5*	*31.8*	*33.0*		
12.7	*27.9*	*29.2*	*30.5*				
11.7	*27.9*						

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A.2.3 Landings

Landings of stairs that have no change of direction are called intermediate landings. A change in direction of 90 degrees results in a quarter-landing (wide L), and a change in direction of 180 degrees produces a half-landing (narrow U). Landings on long flights of stairs are necessary to provide a resting place for stair users, to form turning zones, and, in the event of a fall, to break the force of the fall (**7.2.5**).

The minimum width of the landing must be equal to that of the widest flight of steps that reaches it. The minimum clear depth must equal the widest stair run or 48 inches (1.21 m), whichever is larger.

A.2.4 Headroom

Headroom is measured vertically from the front edge of the nosing of a step to the finished ceiling. It should never be less than 6 feet, 7 inches (2 m).

A.2.5 Length of Run

A stair flight should always consist of three or more risers. The flight should not have too many steps without a landing. In many codes the maximum number of risers permitted in a flight is eighteen (**7.2.5**).

A.3 Develop Configuration Layout

Layout techniques vary in implementation with the configuration chosen, but in all cases, an acceptable and consistent riser and tread relationship should be adhered to in order to provide a layout requiring minimum energy expenditure as well as maximum potential for safety. This section suggests techniques for laying out several types of stair. The following symbols and abbreviations are used:

	Stair	Ramp
H	= Floor-to-floor height	= Elevation change
L	= Length of run between first and last riser nosing	= Length of run from bottom to top
n	= Number of risers	
p	= Number of treads	
R	= Riser height	
G	= Going depth	

A.3.1 Straight Flight Stairs

• Determine floor-to-floor height (H). Select acceptable riser (R) and going (G) dimensions. If space is limited, choose maximum riser (R) and minimum going (G).

• Determine the number of risers (n):

$$n = \frac{H}{R}$$

Set n equal to the nearest whole number, and adjust the riser dimension accordingly.

• The number of treads is equal to the number of risers minus 1:

$$p = n - 1.$$

• The length of run equals the going dimension times the number of treads:

$$L = G \times \mathrm{p}.$$

A.3.2 Flights with Winders and Splayed Steps

By definition, a winder is a wedge-shaped step of varying tread width. To obtain treads of about equal widths, the steps preceding and following the turn may be splayed.

• The narrow portion of the tread should be at least 4 inches (10.2 cm) at a distance of 6 inches (15.2 cm) from the end of the

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tread or inside of the stringer. At the walking line, 10.6 inches (27.0 cm) from the newel or outside handrail, the going must be at least 11 inches (27.9 cm).

- Do not run a step edge into a corner.
- Splayed steps and winders should rise in a clockwise direction where possible. This puts the wide portions of the treads to the right-hand side when going downstairs.

A.3.3 Spiral Stairs

- From 12 to 20 steps can be accommodated in a full circle. The tread angle can range from 30 to 18 degrees.
- Typically, the line of the nosings does **not** radiate out from the geometrical center of the stair but "dances" to some extent.
- The greater the number of steps there are in the circle, the greater is the available headroom clearance but the smaller is the effective going.
- Headroom clearance should not be less than 6 feet, 7 inches (2 m).
- A stair that one ascends in a clockwise fashion has the advantage that, in descent, the handrail is on the right-hand side (**5.3.4**).
- The walking line is taken as 10.6 inches (27.0 cm) from the outside of the newel or the inside of the outer handrail (**2.8**).
- At a distance of 6 inches (15 cm) from the newel or inside stringer, the tread must have a depth that is greater than 4 inches (10.2 cm). At the walking line, the going should not be less than 11 inches (27.9 cm) (**2.8**).
- To develop a dimensionally acceptable layout, proceed as follows:

1. Establish the diameter of the stair and the positions of the first and last risers.
2. Determine the number of risers:

$$n = \frac{H}{R}$$

3. Determine the number of steps and the going dimension at the walking line by using table A.5. The table shows the going dimension where the stair diameter and the number of treads in the plan circle are known.
4. Check the headroom clearance at the most unfavorable point. If the headroom is inadequate, change the number of steps.

A.3.4 Helical Stairs with an Open Well

- A clockwise ascent layout is preferable.
- The actual walking line rise-going dimensions should not exceed acceptable limits.

Table A.6 shows the going dimension (in the direction of the run) at 1-foot (30 cm) intervals from the center of the circle for seven different tread angles. A minimum going dimension of 11 inches (28 cm) should be chosen for the walking line 10.6 inches (27 cm) from the inside or outside handrail.

A.3.5 Ramps

By definition, a ramp is any part of a constructed pedestrian circulation way with a slope greater than 5 percent. Acceptable gradients for ramps depend on the length of ramp to be used and the location of landings.

- To determine if a ramp will be an acceptable solution for an existing site condition, the designer must determine elevation change (H) and the length of run (L). This length is the horizontal distance over which the elevation change takes place, minus the length of any landings.
- If H/L is less than the maximum gradient given in table A.7 for ramps of this length, then a ramp may be used (**3.2.2**). If H/L is

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TABLE A.5

Dimensions for Spiral Stairs: Going Depth at Walking Line[a]

INCHES

Exterior Diameter of Stair	54	60	66	72	78	84	90	96	102
Diameter at Walking Line	32.7	38.7	44.7	50.7	56.7	62.7	68.7		80.7

Number of treads in circle	*Going depth at walking line*[b]											
11	9.22	10.90	12.60									
12		10.01	11.57	13.13								
13		9.26	10.70	12.14	13.58							
14			9.96	11.29	12.63	13.96						
15			9.30	10.55	11.80	13.04						
16				9.90	11.07	12.24	13.41					
17				9.32	10.43	11.53	12.63	13.73				
18					9.85	10.89	11.94	12.98				
19					9.34	10.33	11.31	12.30	13.29			
20						9.81	10.75	11.69	12.63			

CENTIMETERS

Exterior Diameter of Stair	140	150	160	170	180	190	200	210	220	230	240	250
Diameter at Walk Line	86	96	106	116	126	136	146	156	166	176	186	196

Number of treads in circle	*Going depth at walking line*[c]											
11	24.2	27.0	29.9	32.7	35.5							
12		24.8	27.4	30.0	32.6	35.2						
13			25.4	27.8	30.2	32.5						
14			23.6	25.8	28.0	30.3	32.5	34.7				
15				24.1	26.2	28.3	30.4	32.4	34.5			
16					24.6	26.5	28.5	30.4	32.4	34.1		
17					23.2	25.0	26.8	28.7	30.5	32.3	34.2	
18						23.6	25.4	27.1	28.8	30.6	32.3	34.0
19							24.0	25.7	27.3	29.0	30.6	32.3
20							22.8	24.4	26.0	27.5	29.1	30.7

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[a]*Exterior diameter and exterior radius are measured from the inside of the outer handrail of the stair; walking line is estimated as 10.63 inches (27 cm) from the inside of the outer handrail.*

[b]*Going at walking line is calculated from* $2 \sin\alpha/2(r_{ex} - 10.63)$, *where* r_{ex} *is the exterior radius of the stair and* α *is the angle between the front and back lines of a tread. Values to the right of the stepped line are acceptable.*

[c]*Going at walking line is calculated from* $2 \sin\alpha/2(r_{ex} - 27)$, *where* r_{ex} *is the exterior radius of the stair and* α *is the angle between the front and back lines of a tread. Values to the right of the stepped line are acceptable.*

TABLE A.6

Going Dimensions for Helical Stairs with an Open Well

Number of Treads in Circle	*22.5*	*25.7*	*30*	*36*	*45*	*60*	*90*
Tread Angle (degrees)	*16*	*14*	*12*	*10*	*8*	*6*	*4*
Distance from center of circle (feet)	*Going dimension (inches)*						
3	*10.0*						
4	*13.4*	*11.7*					
5	*16.7*	*14.6*	*12.5*	*10.5*			
6	*20.0*	*17.5*	*15.1*	*12.6*	*10.0*		
7		*20.5*	*17.6*	*14.6*	*11.7*		
8			*20.1*	*16.7*	*13.4*	*10.0*	
9				*18.8*	*15.1*	*11.3*	
10					*16.7*	*12.6*	
11						*13.8*	
12						*15.1*	*10.1*
13						*16.3*	*10.9*
14						*17.6*	*11.7*
15							*12.6*
Distance from center of circle (meters)	*Going dimension (centimeters)*						
0.91	*25.3*						
1.22	*33.9*	*29.7*	*25.5*				
1.52	*42.3*	*37.0*	*31.8*	*26.5*			
1.83	*50.9*	*44.6*	*38.3*	*31.9*	*25.5*		
2.13			*44.5*	*37.1*	*29.7*		
2.44				*42.5*	*34.0*	*25.5*	
2.74					*38.2*	*28.7*	
3.05						*31.9*	*21.3*
3.35						*35.1*	*23.4*
3.66						*38.3*	*25.5*
3.96							*27.6*

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greater than the maximum gradient, shorten the length (L) by adding an intermediate landing and check the table again.
• To establish the maximum length of the ramp between landings, consult table A.8 (and see section **3.2.2**).

A.4 Refine and Detail

A.4.1 Step Shape

• *Nosings:* Abrupt nosing overhangs (fig. A.7) and any overhang that is greater than ¾ inch (1.9 cm) should not be constructed (**7.2.10**). Where a nosing is needed, provide backward-sloping nosing overhangs (less than ¾ inch) where this is possible.
• *Wash:* A wash is needed to throw water off external steps. It should not exceed about a 1:60 slope (**7.2.12**).
• *Dimensional regularity:* Risers, treads, and nosing projections must be constructed with a high degree of dimensional consistency, and in fact most building codes wisely insist on this (**7.3**). The differences in dimension between the largest and smallest in a flight and between those in adjoining steps should not exceed 3/16 inch (0.48 cm). This is by no means too exacting a standard for contemporary building practices.

A.4.2 Materials

The appropriate choice of material for stair treads is likely to be influenced by several factors: structural considerations, the type and volume of traffic, appearance, resistance to wear and sometimes chemicals and the climate, ease of maintenance and cleaning, cost, slip resistance, and how comfortable it is to walk on. Avoid soft woods and stone that may erode easily.
• *Floor patterns:* Avoid the use of textures or patterns or nosing strips that make it difficult to discern the edge of the nosings (**7.2.7**). Use colors to emphasize the edge.
• *Carpet fixing:* Avoid step and, particularly, nosing designs that will prevent carpeting from being fixed firmly (**7.2.11**).
• *Slip resistance:* Coefficients of friction (COF) greater than 0.3 may be adequate to prevent slips on level, dry, step surfaces in internal stairs at normal rates of climb, but coefficients of 0.5 are considered preferable and safer. The most critical area for slips is at the nosing, but it is better to ensure that the whole tread has an adequate COF rather than to add abrasive nosing strips that may be visually confusing and may cause trips (**3.6**). Ramps require careful consideration to prevent slips. For a chosen COF for level surfaces, table A.9 shows the equivalent COF that will be required to obviate slips at various ramp gradients. The left-hand column shows a range of coefficients of friction such as might be chosen for a level walkway (**3.5**). The remaining columns show the coefficients necessary to provide equal slip resistance for various ramp gradients (for a person who does not change pace on the ramp).
• *Tread surface:* The surface of stair treads should be smooth, free from projecting joints, stable under the loads with no tendency to shift underfoot, and with nothing to catch the shoe.
• *Injurious materials:* The stair as well as the handrails and balustrading should be free from projecting elements, sharp edges and corners, and any rough surfaces, bars, rods, and other elements that have a small section. Instead, as with the interior of the car, smooth, flat, impact-attenuating surfaces and gentle curves should be used (**7.2.11**).

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TABLE A.7

Acceptable Ramp Gradients, Maximum Rise and Length

Gradient	*Maximum Rise in Single Run*	*Total Length, Excluding Landings*
1:8–1:10	*3 inches (7.6 cm)*	*24–30 inches (61–76 cm)*
1:10.1–1:11	*9 feet (2.74 m)*	*91–99 inches (28–30 m)*
1:11.1–1:13	*14 feet (4.27 m)*	*155–182 inches (47–55 m)*
1:13.1–1:15	*16 feet (4.88 m)*	*210–240 inches (64–73 m)*
1:15.1–1:16	*20 feet (6.10 m)*	*302–320 inches (92–98 m)*

Note: building, fire, and handicapped codes may require different gradients.

Source: Templer et al. (1980).

TABLE A.8

Maximum Length between Landings on Ramps

	Gradient					
Maximum Ramp Length	*1:15.9*	*1:14.3*	*1:13.7*	*1:12.7*	*1:11.6*	*1:10*
IN FEET						
Between bottom and landing 1	*95 (5.9)*	*85 (6.0)*	*80 (5.8)*	*75 (5.9)*	*65 (5.6)*	*45 (4.5)*
Between landing 1 and 2	*75 (10.7)*	*70 (10.9)*	*65 (10.6)*	*55 (10.3)*	*55 (10.3)*	*45 (9.0)*
Between landing 2 and 3	*45 (13.5)*	*45 (14.0)*	*45 (13.9)*	*45 (13.8)*	*45 (14.2)*	
Between landing 3 and 4	*30 (15.4)*	*30 (16.1)*	*30 (16.1)*			
Between landing 4 and 5	*30 (17.3)*					
Between landing 5 and 6	*30 (19.2)*					
IN METERS						
Between bottom and landing 1	*29 (1.8)*	*30 (1.8)*	*24 (1.8)*	*23 (1.8)*	*20 (1.7)*	*14 (1.4)*
Between landing 1 and 2	*23 (3.3)*	*21 (3.3)*	*20 (3.2)*	*17 (3.1)*	*17 (3.1)*	*14 (2.7)*
Between landing 2 and 3	*14 (4.1)*	*14 (4.3)*	*14 (4.2)*	*14 (4.2)*	*14 (4.3)*	
Between landing 3 and 4	*9 (4.7)*	*9 (4.9)*	*9 (4.9)*			
Between landing 4 and 5	*9 (5.3)*					
Between landing 5 and 6	*9 (5.9)*					

Note: figures in parentheses show total height ascended.

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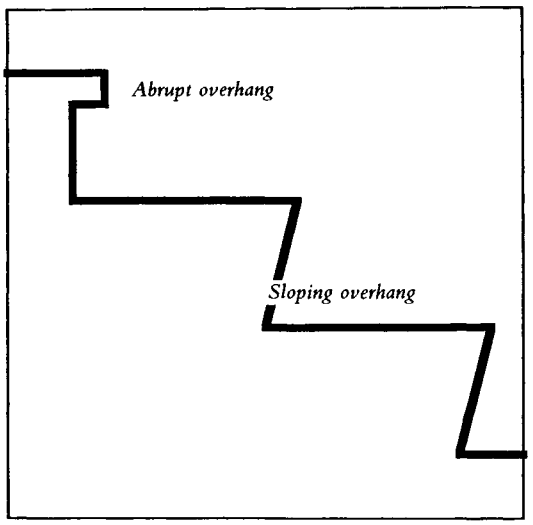

A.7 Nosing overhangs

TABLE A.9

Static Coefficient of Friction for Level Surfaces and for Various Gradients

Level	*1:20*	*1:18*	*1:16*	*1:14*	*1:12*	*1:10*	*1:8*	*1:6*	*1:4*
.80	.89	.90	.91	.92	.95	.98	1.03	1.12	1.31
.75	.83	.84	.85	.87	.89	.92	.97	1.05	1.23
.70	.78	.79	.80	.81	.83	.86	.90	.98	1.15
.65	.72	.73	.74	.76	.78	.80	.84	.92	1.07
.60	.67	.68	.69	.70	.72	.74	.78	.85	1.00
.55	.62	.62	.63	.65	.66	.69	.72	.79	.93
.50	.56	.57	.58	.59	.61	.63	.67	.73	.86
.45	.51	.52	.53	.54	.55	.58	.61	.67	.79
.40	.46	.47	.47	.49	.50	.52	.53	.61	.72
.35	.41	.41	.42	.43	.45	.47	.50	.55	.66
.30	.36	.36	.37	.38	.39	.41	.44	.49	.59

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A.5 HANDRAILS

• *Location:* A stair that is 35 inches (88.9 cm) wide between the walls and with a rail on one side has the maximum feasible width if the rail must fall within the reach of adult users (**6.6**). A 47-inch (1.19 cm) wide stair with handrails on both sides is the maximum width for both rails to be always available to adult users. Current codes permit a single rail for stairs up to 44 inches (1.12 m) and two rails for stairs up to 88 inches (2.24 m).

• *Height:* From the forward edge of the nosing to the top of the handrail should be 36 to 40 inches (0.91–1.02 m), but codes usually require 30 to 34 inches (76.2–86.4 cm). For children, an intermediate rail that is 21.8 to 28.7 inches (55.4–72.9 cm) should be provided (**6.2**).

• *Extent:* Handrails should extend horizontally a minimum of 12 inches (30.5 cm) beyond the top of the stair and beyond the bottom riser for a distance equal to the tread width and then continue horizontally for 12 inches (30.5 cm). The handrails should not project into walkways; the ends should return to the floor or adjoining walls. Handrails should continue along at least one side of a landing.

• *Size and shape:* A 1½-inch (3.8 cm) round handrail is most effective for gripping (**6.3**).

• *Spacing distance from walls:* The clearance between a handrail and an adjoining wall, assuming a circular handrail with 1½-inch (3.8 cm) diameter, should not be less than 3.65 inches (9.3 cm)(**6.5**).

• *Materials:* Handrails should not be too slippery or too rough. Rails that are lightly padded like auto steering wheels can provide the correct range of friction characteristics, may enable better grip forces to occur, and are less likely to cause trauma if they are hit in a fall. Handrail materials should not conduct or retain heat to the degree that they become untouchable. Handrails must not be permitted to deteriorate so their surfaces become splintered or pitted with rust. Finally, the color of handrails should be carefully chosen so they are always highly visible (**6.4**).

A.6 GUARDRAILS

• *Height:* Guardrails should not be less than 42 inches (1.07 m) high unless the width is greater than 6 inches (15.2 cm). In that case, the minimum height of the guardrail should not be less than 48 inches (1.22 m) minus *B*, where *B* is the minimum width of the top surface of the guardrail. Thus, if the width of the top surface of the guardrail is 10 inches (25.4 cm), the height may be 38 inches (0.97 m)—48 inches less 10 inches. The rail should never be less than 30 inches (76.2 cm). The design should discourage people from climbing onto a rail from which they may overbalance and fall (**6.7**).

• *Structural loading:* Most codes require the system to be able to withstand a test load without much deflection. A typical test requires the system to withstand a 200-pound (90.7 kg) vertical load at the midspan of the rail, with a deflection that does not exceed the length of the rail divided by 96. For a horizontal load test, the system may be required to withstand 200 pounds (90.7 kg), measured at the top of the rail at its midspan, with a deflection that does not exceed the sum of the rail height divided by 24 plus the rail length between vertical supports divided by 96. When the load is applied at a vertical support, the deflection may not exceed the rail height divided by

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12. In public buildings, there is a greater danger of extreme loading, so a higher standard of structural strength is required. The test load is increased by 50 percent (or 65 percent in some circumstances such as balconies). For one- and two-story residential buildings, the test load may be reduced by 50 percent (**6.9**).

• *Baluster spacing:* It should not be possible to pass a sphere of 3½-inch (8.9 cm) diameter through the balustrading (**6.9**).

A.7 ILLUMINATION

• Adequate illumination, either natural or artificial, must be provided. The IES recommendation of 5 to 20 footcandles (54–215 lux) for most applications seems to be much more realistic for stair safety than those minima permitted by most building codes. A minimum of 8 footcandles (86 lux) may be adequate.

• The illumination should be reasonably constant over the whole stair.

• Window and artificial light sources should not be placed where the stair user must include them and the steps in the same direct field of vision, and shadows on the steps should be avoided.

• For reflectance, the IES recommends 21 to 31 percent for floors.

• If the stair is located where there is any risk that someone might stumble into it unexpectedly, permanent supplementary artificial illumination should be provided.

• The switches that control the stair lights should be placed sufficiently far from the stair so there is no risk of a person's falling while reaching for the switch. Three-way switches should be used at the top and bottom of the stairs (**7.2.8**).

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NOTES

1 THE CHARACTERISTICS OF STAIR FALLS AND INJURIES

1. This does not include falls in or from transport vehicles or while boarding or alighting from them.

2. Archea et al. (1979) provide a comprehensive listing of accident causes discussed in the literature from 1960 to 1979. Further evidence is provided in Templer et al. (1978, 1985).

3. A study entitled "Fundamental Studies in Reducing the Severity of Injuries from Stairway Falls" is underway at the Georgia Institute of Technology with funding from the National Science Foundation. John Templer, Satya Hanagud, and Toby Boulet are the principal investigators. The study will develop a computer model of stair falls.

2 RISER AND TREAD GEOMETRY FOR COMFORT AND SAFETY

1. The other linear measure in use in France at the time—the Roman foot—seems to have been used mainly in the cloth industry (Skinner 1967).

2. Olmsted (1911) names some of the authors but without references and not always correctly.

3. Equations 2.6 and 2.7 have appeared in many editions of *Time Saver Standards* (see Callender 1982)—with an error in equation 2.6 that has been incorrectly copied from Freeze's original formula. *Time Saver Standards*' version of 2.6 is

$$R = 9 - \sqrt{1/7(G-8)(G-2)}.$$

4. Olmsted (1911). When this paper was published, the more famous Frederick Law Olmsted, Sr., was dead; it is possible that the paper is by the younger Olmsted.

5. The equation for men is as follows:

$$\log_e Y = 0.0417993918\ V\cos\theta + 0.0005876207\ WR\sin\theta - 0.0009464963\ WT\sin\theta - 0.0002390824\ (V\cos\theta)^2 + 0.0003753539\ VT\cos\theta + 0.4385368671\ \theta^2 - 2.142576059$$

The equation for women is:

$$\log_e Y = 0.0253402476\ V\cos\theta - 0.0010823549\ WT\sin\theta + 0.003480929 R^2 - 0.0007577114\ T^2 - 1.485224153$$

And the equation for all the subjects is:

$$\log_e Y = 0.0453353942\ V\cos\theta - 0.2907272046\ WV\sin\theta\cos\theta - 0.0002056409\ (V\cos\theta)^2 - 0.0011300552\ WT\sin\theta + 0.0012330934\ WR\sin\theta - 2.049299478$$

Where Y = kilocalories per minute per kilogram
V = velocity of climb (vertical) (feet per minute)
θ = angle of stair to horizontal (radians)
R = riser height (inches)
W = weight (kilograms)
T = tread (inches)

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GLOSSARY

Baluster: a post in a balustrade of a flight of stairs that supports a handrail (from the Italian *balausto*, the wild pomegranate whose double-curving calyx tube the baluster often resembled).

Balustrade: the whole infilling from handrail down to floor level at the edge of a stair.

Banister: a baluster (corruption of *baluster*).

Circular stair: a helical stair.

Dextral stair: a stair that turns to the right during ascent.

Dog-legged stair (or dogleg): a stair with two flights separated by a half-landing, and having no stairwell, so that the upper flight returns parallel to the lower flight.

Double-return stair (or side flight): a stair with one wide flight up from the lower floor to the landing and two flights from the landing to the next floor.

Ergonomics: the interaction between work and people, particularly, the design of machines, chairs, tables, etc. to suit the body and to permit work with the least fatigue.

Flight: a series of steps between landings.

Going: the horizontal distance between two successive nosings. (In a helical stair the going varies.) The sum of the goings of a straight flight stair is the going of the flight.

Gradient of a stair: the ratio between going and riser; the angle of inclination.

Guardrail: a protective railing designed to prevent people or objects from falling into open well, stairwell, or similar space.

Handrail (or guardrail): a rail forming the top of a balustrade.

Helical stair: the correct but not the usual name for a spiral stair.

Landing: a platform at the top, bottom, or between flights of a staircase.

Mopstick handrail (or mopstick): a handrail that is circular except for a small flat surface underneath.

Newel (or newel post): the post around which wind the steps of a circular stair. Also applied to the post into which the handrail is framed.

Nosing: the front and usually rounded edge to a stair tread. It frequently projects over the riser below it.

Nosing line: a line touching the lead edges of the nosings of successive treads of a stair.

Nosing overhang: the distance that the nosing edge of a step projects beyond the back of the tread below.

Ramp: an inclined plane for passage of traffic.

Riser: the upright face of a step.

Riser height (or rise): the vertical distance from the top of a step at the nosing to the top of an adjoining step at the nosing.

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Sinistral stair: a stair that turns to the left in ascent.

Spiral stair (or helical stair): a circular stair in which all the treads are winders.

Stair: (1) a series of steps with or without landings, giving access from level to level; (2) one step, consisting of tread and riser.

Stairway: a staircase, or a stairwell.

Step: one unit of a stair, consisting of a riser and a tread. It may be a flier or a winder.

Stepladder: a ladder built with rectangular stiles and treads (not rungs) that are designed to be horizontal in use (*see also* Steps).

Steps (or pair of steps): a stepladder with a framed stay hinged to the top to make it self-supporting.

String (or stringer): a sloping board at each end of the treads that carries the treads and risers of a stair.

Tread: the (usually) horizontal surface of a step; also the length (from front to back) of such a surface.

Wash (or kilt): a slight sloping of treads to throw off rainwater.

Winder (or wheel step): a tread of triangular or wedge shape.

Winding stair: a spiral stair, a circular or elliptical stair with a well at the center.

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